DESIGNING AN APPROACH FOR SUSTAINABLE LANDSLIDE INVENTORY MAPPING IN NEPAL

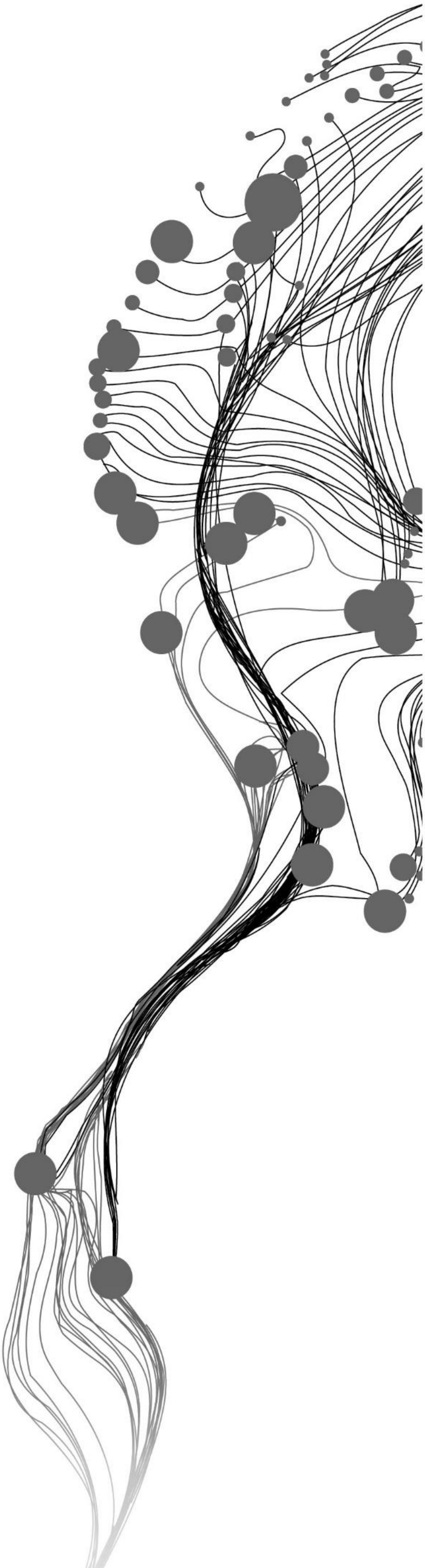
SANSAR RAJ MEENA

APRIL, 2017

SUPERVISORS:

Dr. Cees J. Van Westen

Dr. Olga Christina Mavrouli



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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

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SUPERVISORS:

Dr. Cees J. Van Westen

Dr. Olga Christina Mavrouli

THESIS ASSESSMENT BOARD:

Professor, Dr. V.G. Jetten (Chair)

Dr. Rens. van Beek, External Examiner, Utrecht University

ABSTRACT

Landslide inventory in Nepal is currently not done in a continuous and coherent manner, and efforts are made after major triggering events only, such as the 2015 Gorkha earthquake. There is a lack of sharing of knowledge and cooperation among stakeholders to coup with significant disaster events. This research will focus on filling those gaps by designing an approach for sustainable landslide inventory mapping in Nepal and testing this out in a sample area in the southern part of the Rasuwa district. The overall framework of research is to make a conceptual design of a National landslide information system for Nepal and to show how different stakeholders can be involved. The use of a National landslide information system, to report and provide landslide data would benefit the stakeholders involved in data collection and landslide management. Several stakeholders could be considered such as road department, land management authority, forestry department, disaster management department and army. These stakeholders have different data requirements and are determined in this research. The landslide database system should be designed in such a way that it can incorporate information about different landslide characteristics and types. Availability and extraction of landslide data from the database are the important aspects. The landslide characteristics to be comprised in the database are defined, such as the completeness, the form of representation, the date of occurrence, the subdivision in scarp and accumulation areas, and the type of landslides. Based on field investigations and literature reviews the optimal format of the landslide database is determined for the National landslide information system for Nepal.

For the reporting of landslides directly in the system, a web portal is proposed that will be connected to the internet and the central database with GOOGLE EARTH or another interface on it. Stakeholders who can contribute to the reporting of landslides are identified by field interviews and questionnaires. For example, simple users like school teachers can report a landslide event by pointing it out in the system as schools at the district level have the required infrastructure and internet facilities. Schools can also organise meetings with the student regarding collecting information of any landslide event occurred in nearby areas, and then register it with the system. Also, different methods for generating the inventory data are analysed in this thesis, and the applicability and efficiency of various collection methods are tested, including, image interpretation, the use of field-based Tablet PC, interviews and field survey. Several data collection tools were tested in a sample area in southern part of Rasuwa district. An unmanned aerial vehicle (UAV) was used and tested near Mailung village. GIS-based tablet PC is also used to map landslides in the area, focusing mainly on landslides that occurred after the monsoon rains. Interviews were carried out focusing on farmers and village residents and local police officers. Available landslide inventories for Gorkha event were collected and to see the spatial coverage of landslides in the country. Effects of different quality and completeness levels of landslide inventories, using tools such as Frequency Area Distribution and spatial overlap were carried out.

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1. INTRODUCTION

1.1. Background

In Nepal, many landslides occur every year during the monsoon period. Landslides are also triggered by earthquakes, and the situation may worsen during the subsequent monsoon rains and lead to the substantial destruction of infrastructure, human losses and property damage in the country. During the 2015 Gorkha earthquake, amongst several others a major landslide took place in the Langtang valley which completely buried the whole village of Langtang. The figure shows the pre and post-event satellite imageries of the Langtang area with new triggered landslide marked in a yellow circle that buried whole Langtang village. It is estimated that about 430 people were killed in that landslide event (OSOCC, 2016).

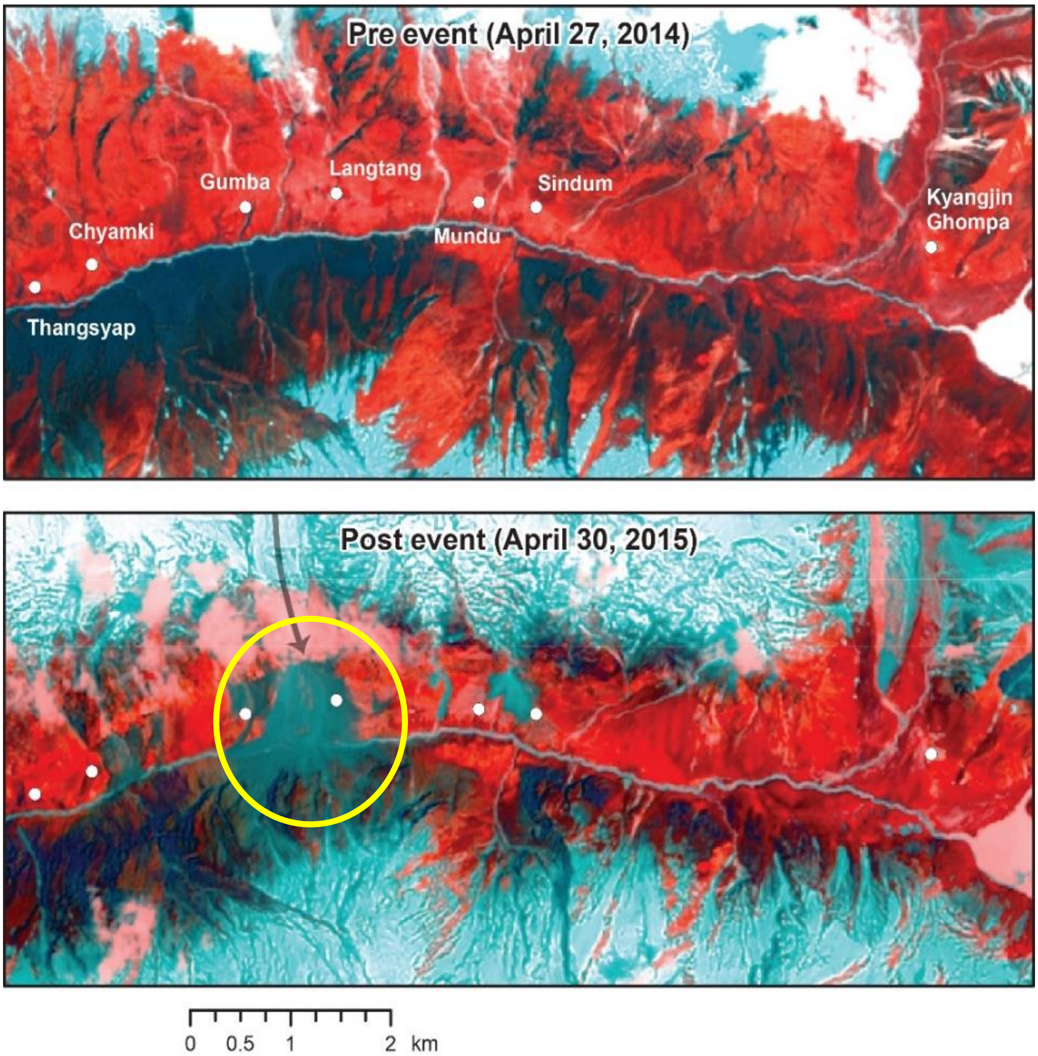


Figure 1.1 Shows pre and post Gorkha event satellite imageries with landslide (Yellow circle) in Langtang area(Greicius 2015).

After the earthquake some regions became inaccessible. Hence it was tough to get the overview of the danger, and the amount of damage it caused. Almost two years after the Gorkha earthquake, the reconstruction phase is still under consideration and not implemented.

Petley et al. (2007) and Petley 2017a collected data about the loss of human life due to the occurrence of landslides. His database contains statistics of loss of life from 1980 to 2016 using various sources including government datasets, scientific papers, newspaper reports, NGO reports(Petley et al. 2007; Petley 2017a). According to (Petley 2017a) regarding landslide events that caused loss of life, excluding earthquake-induced events, 2016 was the worst year in the dataset for the last 36 years. A total of 61 fatal landslide events were recorded in 2016, whereas the last worst year was in 2002 with 58 events, and then 49 events in 2009 (Petley 2017a). Landslides in 2016 led to 184 fatalities (Petley 2017a)). There were a significant number of small events in 2016. The general pattern of damaging landslides with fatalities in the course of the most recent ten years remains linear, indicating that there is no improvement at lessening landslide losses in the nation.

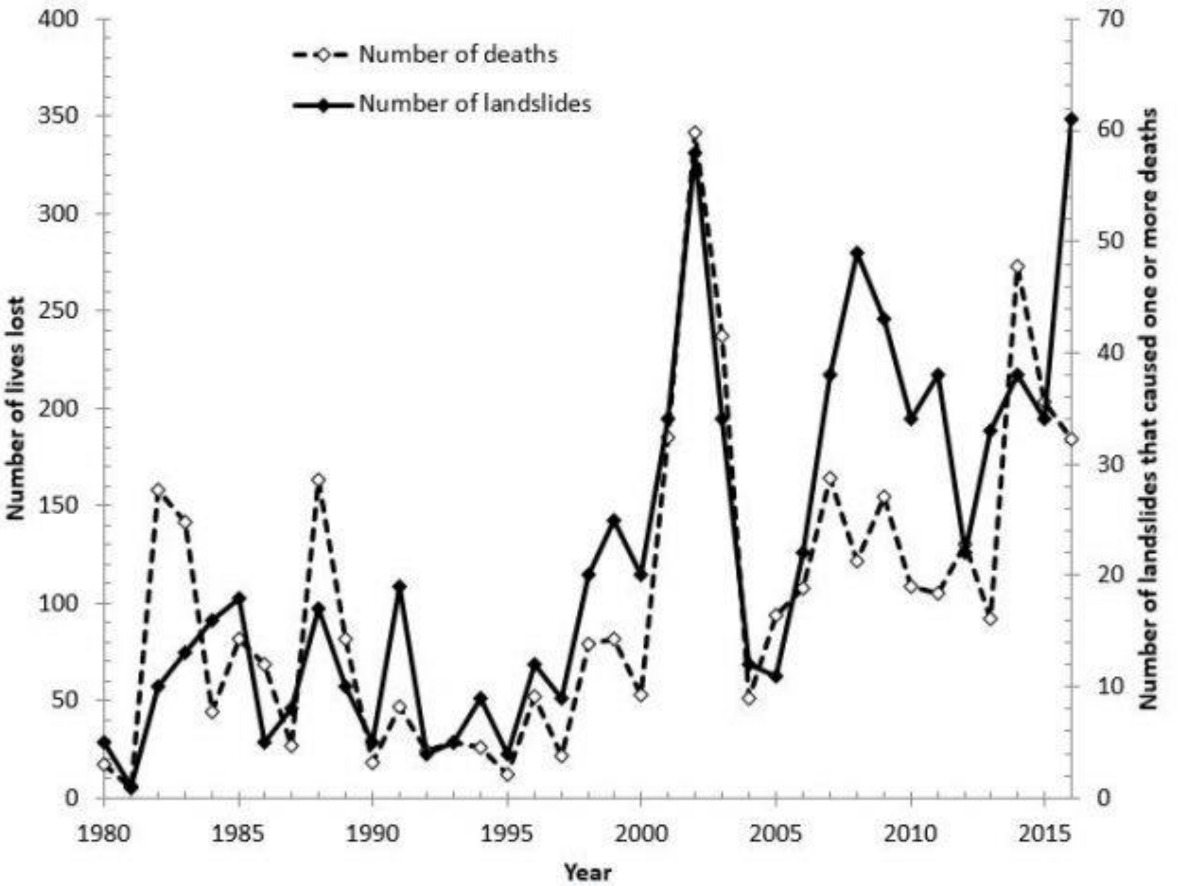


Figure 1.2 Showing the number of fatal landslides and the number of deaths per year in Nepal since 1980 to 2015(Petley 2017a)

In the Gorkha earthquake event, the main shock of 25 April 2015 and the aftershock of 12 May 2105 caused the death of more than 9000 people(Shrestha et al. 2015). There is a lack of capacity of responding after the disaster event in government agencies which are working in disaster risk reduction like District Natural Disaster Committee, Army, and various other organisations and NGOs. The increase in landslide casualties takes place as the result of limited investments in slope protection, and that spatial planning is almost absent, let alone regional planning that tries to avoid landslide damage. Also, that information on landslide occurrence is not collected and stored in a coherent manner.

However, for better and efficient management of landslide hazard in the country, the government of Nepal should take steps towards the development of a landslide information system for Nepal. Such a platform will provide researchers and policy developers with a system for landslide zonation of the country and most potential regions for quick response during landslide hazards. Currently, there are some organisations like Tribhuvan University and ICIMOD who have prepared pre-earthquake (Pokharel & Bhuju 2015)and post-earthquake(Gurung & Maharjan 2015) landslide inventories. However, the access to these inventories is limited. So, there is a need for cumulative effort to make a national level landslide information system.

1.2. Research Objectives

The main objective of this work is to make a conceptual design for a continuous landslide inventory system for Nepal and to test the different methods for landslide inventory mapping in a sample area of Nepal, in Rasuwa. The following sub-objectives were formulated accordingly:

1) Evaluation of different data collection techniques for landslide mapping.

2) Evaluation of the effects of different quality and completeness levels of landslide inventories, using tools such as Frequency-Area Distribution and spatial overlap.

3) Identification of users of the system and identification of their roles and their requirements.

4) Identification of providers of the landslide information for the system.

5) Design of the framework of a Web-GIS multi-level structure for the landslide information system, which can be useful for collecting, updating and managing landslide data efficiently.

1.3. Sub-objectives and Research Questions

1) Evaluation of landslide inventorying techniques.

- Which will be the field-based method for collecting landslide information in the rugged terrain areas of Nepal?
- Is it possible to organise local landslide reporting at local VDC level in Nepal?
- How to involve the local community in landslide mapping using interviews and other methods?

2) Analysis of Inventories

- How to check the landslide inventories regarding completeness and quality?
- How to compare them?

3) Identification of Users of the system.

- If Nepal has to develop a landslide database system then who will be the users and what are their roles, and which data requirements do they have?

4) Identification of providers of the System

- Who will be the providers of landslide information at various levels in Nepal?
- What are the characteristics of the data for the providers, and which tools are used?

5) Design of the WebGIS System.

- How to develop an optimal landslide database structure and to incorporate information on reactivation of landslides after monsoon?

1.4. Methodology

1.4.1. Inventorying techniques

For a collection of landslide data, several data collection tools were used in the field in southern part of Rasuwa district. For mapping landslides after 2015 Gorkha earthquake satellite image interpretation is carried out with the use of google earth imagery created after assembling pictures of the study area together and later georeferenced. High-resolution satellite imagery was very useful in delineation of landslides after the earthquake. For mapping landslides after monsoon 2016 in the field windows based tablet PC was used with ArcGIS software with a base map created using google earth imagery. Using tablet in the field along with topo maps and GPS locations helps in identification of the location of landslides. Tablet PC allows the direct mapping of landslides at the field level without waiting for getting cloud-free images after monsoon period in Nepal. For a collection of historical landslide information, local village people were interviewed based on a landslide information sheet used during the field survey.

1.4.2. Analysis of landslide inventory

After collecting data and preparing landslide inventory for the study area, analysis of existing landslide inventories regarding completeness and quality is carried out. For doing analysis first landslide inventories for the commonly cropped region in the southern part of Rasuwa district is selected and comparison of inventories regarding completeness and quality is discussed. Later in other section, five point based landslide inventories from Gorkha event are analysed to see the differences in mapping for the same event and also the extent of the work done for the same event. In Figure 1.3, a flow chart showing the steps of the methodology are described.

1.4.3. Identification of Stakeholders

In this section stakeholders of the landslide, information system are identified based on interviews, surveys and literature review. Landslide data users and their requirements from the system are identified.

1.4.4. Identification of data providers

Data providers for the system are also identified, and standard data formats and guidelines for landslide data collection are decided., also based on interviews, surveys and literature review.

1.4.5. Database structure

For the development of conceptual database structure of the National landslide information system in Nepal, information regarding users and providers are crucial. Data requirement and guidelines for mapping landslides are important aspects of the system along with updating datasets at regular interval. Recommendations and suggestions based on the questionnaire were crucial for the development of the system. Data redundancy and data from different sources in various formats are the challenges in the development of the system.

1.4.6. Landslide reporting

For identification of potential groups of stakeholders who can report landslide in Nepal field interviews and questionnaires were carried out. Organisation related to landslide management in Nepal were visited, and officers from these organisations were interviewed. Also, a policeman at Haku village development committee was interviewed, and it was found that police at the local level is the main source of information related to any hazard in the local area. School at Haku village and Dhunche headquarters were visited, and it was found that schools already have disaster management in their educational curriculum and teachers were using new technology including social media and Google Maps services.

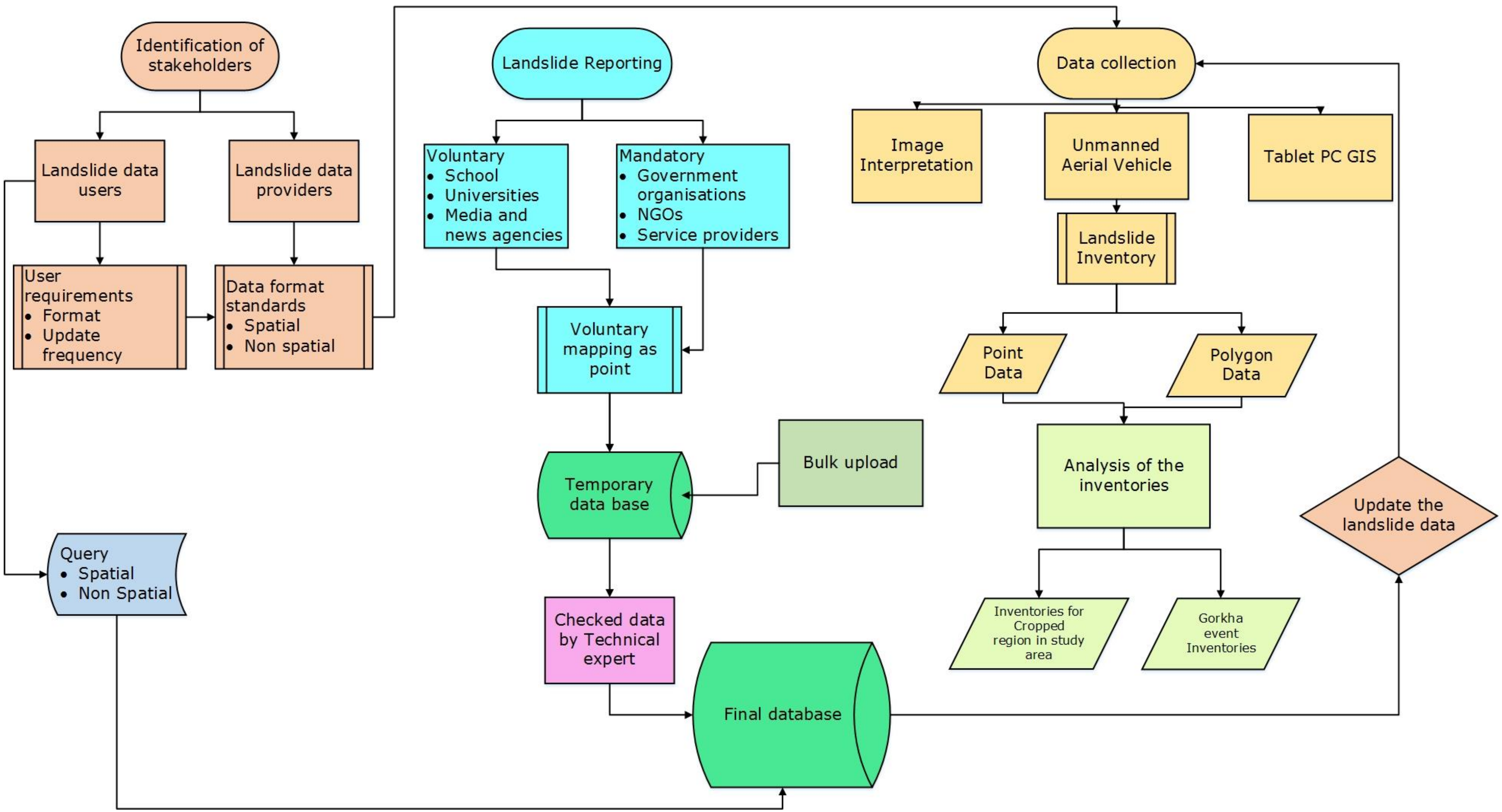


Figure 1.3 Methodological flowchart

2. LITERATURE REVIEW

2.1. Landslide inventory

Landslides are common hazards in the mountain regions all over the world. Given the landslides variable characteristics, they cause enormous damage to human life and infrastructures. Landslides can involve several actions like sliding, toppling or falling of rocks and debris down the slope, or they can include the combination of several movements during the occurrence of it(Cruden et al., 1996). Precipitation and earthquake are common physical triggers for landslides. In the Himalayan region, rainfall in the monsoon period triggers landslides every year (Dhital et al., 1993). Landslides triggered by earthquakes are severely destructive. Recent global landslide triggering events are Wenchuan earthquake China (Cui et al., 2011), Gorkha earthquake Nepal (ICIMOD, 2016) and Bihar earthquake India(Keefer, 2002). These events reveal that the countries highly vulnerable to landslides are in the developing world(van Westen et al., 2013).There is always lack of information on triggering factors affecting landslides in an area(Hervas, 2009). For understanding the factors, there are several key aspects of tracking, recording and analysing data(Klose, Damm, & Highland, 2015).

There are many definitions available for landslide inventory in the literature. According to (Guzzetti et al. 2012), landslide inventory maps are the basis for obtaining the records of the date of occurrence, location and type of slope movements. (Parise 2001) described landslide inventory as a map that represents the spatial distribution of mass movements. (Eeckhaut & Legorreta 2013). A landslide inventory gives information about type, size location, activity, date, causal factors and damage. In a landslide inventory past landslides are characterised and distributed in the detailed register (Hervás 2013). A dataset of landslide inventory can provide information on the time of the event, the location of occurrence, type of landslide and the extent of the landslide(Stanbrough 2013). A GIS-based landslide inventory allows collection, management, analysis and publishing of a large amount of data in a region(Colombo et al. 2005).

As given by (Guzzetti et al. 2012) landslide inventories preparation depends on their purpose, the scale of base maps, the extent of the study area and available resources(Guzzetti et al. 2000).

i. For documenting the spatial extent of landslide phenomenon at various levels ranging from small scale to large scale areas(Tapas R. Martha et al. 2016; Zhang et al. 2016; Godt 2016; Gnyawali & Adhikari 2016).
ii. Landslide inventory is the fundamental step that leads to landslide susceptibility and risk assessment.(van Westen et al. 2005; Martha et al. 2013; Guzzetti 2005).
iii. To determine the types, distribution, and pattern of landslides about geological and morphological characteristics(Rautela et al. 2014).
iv. Evolution of landslides mainly dominated by mass wasting processes (Damen & Krol 2015; Malamud et al. 2004c; Stark & Guzzetti 2009).

Several suggestions and indications by Guzzetti et al. (2012) for preparing landslide inventories; these assumptions are described as:

a) A landslide event landslide leaves visible traces that can be observed using satellite imageries, aerial photographs and digital surface models (Guzzetti et al. 2000; Nichol et al. 2005; Sato et al. 2009; Zhi et al. 2014; Tapas R. Martha et al. 2016; Tiwari et al. 2017). Most of these signs refer to changes in the morphology e.g. form, position, shape and topographical surface(Guzzetti et al. 2012).
b) The same type of mass movement results in a similar landslide signature. From the visual appearance of a landslide, qualitative information of the slope failure can be inferred.

c) Slope failures are the consequence of the interaction of physical procedures, and mechanical laws controlling the stability or failure of a slope(Guzzetti et al. 2002).
d) Slope failure probably happens under the conditions that prompted past instability. In this way, acknowledgement of recent slope failures is imperative to recognise sites of future failures (Guzzetti et al. 2012).

Landslide inventorying is the basis of determining risk management (Ghosh et al. 2009; Fell et al. 2008; van Westen et al. 2005; Aleotti et al. 1999). Golovko et al. (2014) analysed multiple sources of slope failures for the establishment of a comprehensive multitemporal landslide inventory. He also described landslide inventories as the prerequisite that enables the landslide hazard assessment. Landslide inventories are crucial for susceptibility models that predict landslides by past conditions. Especially it is important to record information on occurrence date to link with triggering factors. Also, spatial location and typology of the landslide are crucial. Inventory maps can give information about probably threatened areas to disaster management authorities that can be used for reconstruction planning after an earthquake

2.1.1. Landslide inventory methods

The process of preparation of landslide inventory has evolved from paper sheets and maps obtained from field work to observation of satellite imageries(Hervas 2009; STONE 1964) and historical data (Bogoslovsky & Ogilvy 1977; Hervas 2009). Recently the availability and use of high-resolution remote sensing optical images (Schweigl et al. 2013) have them shown to be very useful in the identification of landslides. For instance, single triggering events like earthquakes trigger thousands of landslides at the same time. Therefore, remote sensing plays a major role in mapping and analysing them. Another important event is rainfall induced landslides like the ones that are occurring in a monsoon are less frequent and are harder to map from images because of unavailability of optical images mainly because of cloud cover. Good quality pre and post-landslide event satellite images are required for conducting classification and interpretation of the hazard affected area. There have been several attempts to map landslides using automatic and semi-automatic classification techniques Pixel based versus object-oriented (Martha et al. 2010). Scientific progress towards the pixel based automatic identification of landslides has been made using passive or active remote sensing imageries (Schweigl et al. 2013). Considerable progress towards the pixel based automatic identification of landslides has been achieved using passive or active remote sensing imageries (Margottini et al. 2013). Borghuis et al. (2007) used unsupervised classification, and it resulted in detecting about 60% of manually mapped landslides. Other researchers like (Nichol et al. 2005) used change detection methods to differentiate landslides from false positives like bare land, and bedrocks (Drăguţ et al. 2006) stated that Object-oriented analysis is capable of integrating spectral, elevation data and has the ability for automatic classification of landforms. The object-oriented classification has better potential than pixel base classification (Drăguţ et al. 2006). Similarly, DEM derived data such as the slope gradient; texture is essential for the automated classification of terrain (Iwahashi & Pike 2007) Lidar-derived data is also very useful for landslide identification and updating (Schweigl et al. 2013). The accuracy of Digital Terrain Models is an essential factor as it has derivatives like the slope, terrain curvature, and flows direction. These derivatives lead to detection and classification of landslides (van Westen et al. 2013). For making better and accurate analysis of a certain geographical phenomenon, it is important to use spatial tools directly in the field (Mauro De Donatis et al. 2006). There are several tools used worldwide for obtaining information on landslide events like the news, diverse media, web alerts, as well as the involvement of local people(Baum et al. 2014) through focused or random interviews. Also participatory mapping including transect mapping, scale mapping (Mwanundu 2009), is essential in data collection.
Other tools like the use of GIS-based tablet mapping are also very critical in geological mapping units and also for hazard assessment mapping. There are applications developed by different scientific organisations,

namely SIGMA Mobile, a digital field mapping application by British Geological Survey(Colm J. Jordan 2015) and GEOPAD by the University of Michigan (Knoop & van der Pluijm 2006) to this end.

Unmanned Aerial Vehicle (UAV) is a potentially effective tool for collecting information about landslides at site-specific scale. It is also complementary to other techniques like radar and laser scanning because it is cost effective. Also during cloud cover, it is tough to get optical satellite images so UAV can be used in those conditions (Stumpf et al. 2013). There are benefits of using UAV like it is a fast and efficient way to get spatial information of any area. Ultra high-resolution of about 5cm of images taken by UAV in a study carried out by Turner et al. (2012)can allow quantitative analysis of surface and also allows the evolution and spatial distribution of small surface features(Kargel et al., 2016; Walter et al., 2009). Usability of UAVs has increased rapidly after the devastating Gorkha earthquake of April 2015 UAV have been used for characterization of landslides (Clark et al. 2016).

According to Palenzuela et al. (2015) altimetry is the basic tool for quick mapping of landslide features that allows coverage of inaccessible areas in semi automatic way(Guzzetti et al. 2012). The laser altimetry has evolved in past decade which is based on (LiDAR), that enables preparation of high resolution digital elevation models. The (HRDEM) have been used for the evaluation of land changes(Tech 2015; Iwahashi & Pike 2007).

Table 1.1 presents different landslide mapping techniques and their applicability at various scales.

Table 2.1 Landslide mapping techniques and their applicability at various scales source:(charim 2017).

Group	Technique	Description	Scale		
			N	L	S
Image interpretation	Stereo aerial photographs	Analog format or digital image interpretation with single or multi-temporal data set	M	M	M
	High Resolution satellite images	With monoscopic or stereoscopic images, and single or multi-temporal data set	H	H	H
	LiDAR shaded relief maps	Single or multi-temporal data set from bare earth model.	H	H	H
(Semi) automated classification based on spectral characteristics	Aerial photographs	Image ratioing, thresholding	M	M	M
	Medium resolution multi spectral images	Single data images, with pixel based image classification or image segmentation	H	H	H
		Multiple date images, with pixel based image classification or image segmentation	M	M	M
(Semi) automated classification based on altitude characteristics	InSAR	Terrestrial Radar Interferometry	M	M	M
		Permanent scatterers for pointwise displacement data	L	L	L
	LiDAR	Overlaying of LiDAR DEMs from different periods	L	L	L
	Photogrammetry	Overlaying of DEMs from airphotos or high resolution satellite images for different periods	L	L	L
Field investigation methods	Field mapping	Conventional method	H	H	H
		Using Mobile GIS and GPS for attribute data collection	H	H	H
	Interviews	Using questionnaires, workshops etc.	H	H	H
Archive studies	Newspaper archives	Historic study of newspaper, books and other archives	M	M	M
	Road maintenance organizations	Relate maintenance information along roads caused by landslides	H	H	H
	Fire brigade/police	Extracting landslide occurrence from logbooks on accidents	H	H	H
Dating methods for landslides	Direct dating method	Dendrochronology, radiocarbon dating etc.	L	L	L
	Indirect dating methods	Pollen analysis, lichenometry and other indirect methods,	L	L	L
Monitoring networks	Extensometer etc.	Continuous information on movement velocity using extensometers, surface tiltmeters, inclinometers, piezometers	L	L	H
	EDM	Network of Electronic Distance Measurements, repeated regularly	L	L	H
	GPS	Network of Differential GPS measurements, repeated regularly	L	L	H
	Total stations	Network of Theodolite measurements, repeated regularly	L	L	H
	Ground-based InSAR	Using ground-based radar with slide rail, repeated regularly	L	L	H
	Terrestrial LiDAR	Using terrestrial laser scanning, repeated regularly	L	L	H

2.2. Landslide Management Systems Worldwide

Landslide databases give vital information on landslide areas, triggers, geometry and a large scope of extra attributes(Malamud et al. 2004a; Fell et al. 2008; Van Den Eeckhaut & Hervás 2012). They are considered especially vital for susceptibility analysis and hazard evaluation and risk assessment as they provide the base data for carrying out susceptibility analysis(van Westen et al. 2005), and they are the basis of landslide studies done at various spatial levels from regional to national levels (Guzzetti et al. 1999; van Westen et al. 2003; F. Guzzetti & Tonelli 2004; Francisco et al. 2010; Van Den Eeckhaut & Hervás 2012). Landslide databases constitute of core attributes, supplementary data and complementary information (Hervás 2013). Core attributes are location, landslide type, date of occurrence(Hervás 2013). Supplementary data contains landslide geometry, geology, land use(Hervás 2013). Complimentary data incorporates illustrations, aerial photos, monitoring data (Hervás 2013). For every landslide, the accessible data should be transferred to software that is organised to gather and store data so that clients can retrieve, include, update or expel information in an automated way. Analysis based on huge sets of multi-connected information can bring about various issues when putting away as documents like duplicity and deviation (Yeung & Hall 2007; Klose et al. 2014).
In natural hazards domain, numerous endeavours are made to make databases lately, for instance, earthquakes (Kadirioğlu et al. 2016), tsunami (Schaefer et al. 2016), elements at risk (Risicokaart 2017), and floods (Jak & Kok 2000). The landslide blog updated by Petley (2017b) is a comprehensive collection of landslides that caused damage and casualties. Petley (2017b) started compiling data related to landslides since 2002 that cause human fatalities around the world, in 2007 he started his blog to raise the awareness of landslide hazard and to connect the international landslide community. EM-DAT (CRED 2016) shows the information of the events in which at least ten persons died or at least 100 people were affected, asking for international help. A study carried out by Van Den Eeckhaut & Hervás (2012) in Europe shows the status of landslide databases and value for attaining landslide susceptibility hazard and risk analysis. It indicates that a total of 25 European Union members maintains the national landslide databases.

In Europe, France created the digital landslide database in 1994 developed by French geological society (BRGM 2017). Some countries like Italy have two landslides databases: IFFI(Trigila et al. 2010) and AVI (Fausto Guzzetti & Tonelli 2004). In Great Britain, there is a National landslide database (Pennington et al. 2015) that is developed by the British Geological Survey. It has point and polygon based landslide information with attributes attached with information for each landslide; it constitutes over 17000 records of landslides in Great Britain.

Table 3.1 shows some examples of landslide databases outside Europe. One of them is from Nicaragua and has been developed by the Nicaraguan geoscience institute (Devoli et al. 2007). The web interface of recently developed landslide information system for Colombia is an excellent example of how landslide data should be visualised. The webGIS interface is user-friendly, and users can switch between different layers and select the information that they want the example of web interface for Colombia is given in figure 1.4. For reporting of landslides directly into the system, there are three simple steps the first user have to fill basic information about landslides and then can enter a location by putting coordinates or by pointing it on the map. People could also enter information about the type of landslide and damage caused.

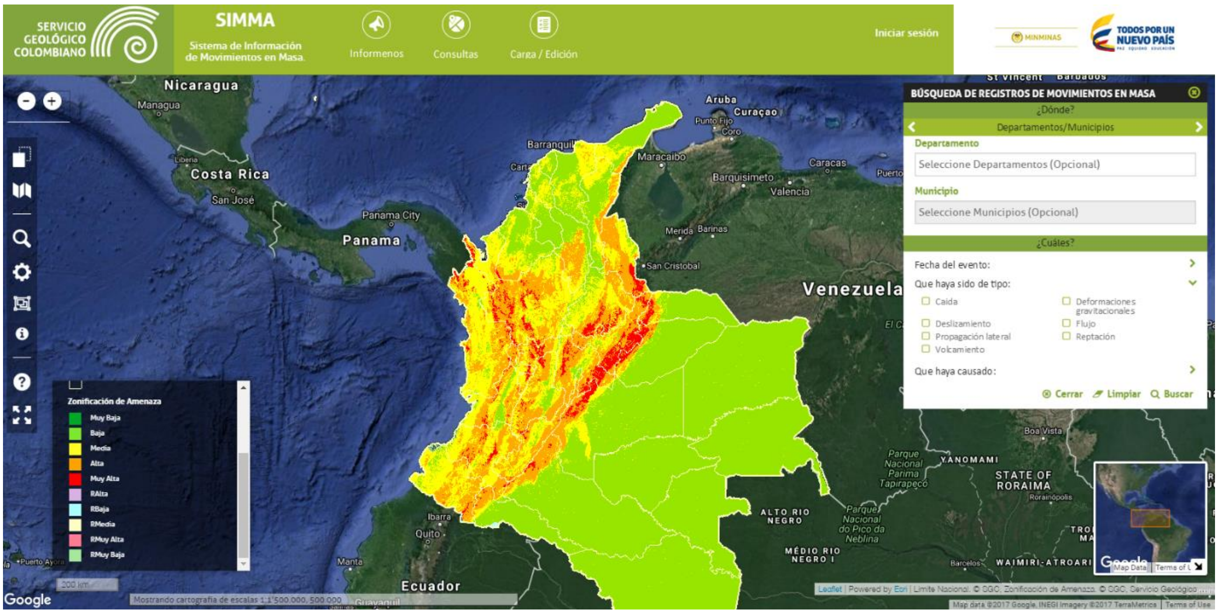


Figure 2.1 Showing web GISinterface of SIMMA Colombia

Table 2.2 Examples of Landslide information systems worldwide.

No	Country	Database name	Holder (not necessarily producer)	Weblink
1.	Republic of Colombia	SIMMA - Sistema de Información de Movimientos en Masa	Colombian Geological Survey	http://simma.sgc.gov.co
2.	Great Britain	BGS National Landslide Database	British Geological Survey	http://www.bgs.ac.uk/landslides/NLD.html
3.	Ireland	GSI National landslide database	Geological Survey Ireland	https://dcenr.maps.arcgis.com/apps/webappviewer/index.html?id=b68cf1e4a9044a5981f950e9b9c5625c
4.	New Zealand	New Zealand Landslide Database	GNS Science	http://data.gns.cri.nz/landslides/wms.html
5.	California (United States of America)	The California Landslide Inventory	California Department of Conservation	http://maps.conservation.ca.gov/cgs/lsi/

6.	Tasmania	Landslide Database	DEPARTMENT of STATE GROWTH	http://www.mrt.tas.gov.au/portal/landslide-database
7.	Commonwealth of Australia	LANDSLID Australian Landslide Database	Geoscience Australia	http://data.gov.au/dataset/3f835bb3-014c-4138-85e5-bc9b33d70640
8.	Oregon (United States of America)	Statewide Landslide Information Database for Oregon (SLIDO)	The State of Oregon	http://www.oregongeology.org/slido/index.html

2.3. Landslide inventories for Nepal

In this section listed available landslide inventories for Nepal that are collected during fieldwork. There are many other landslide inventories, but they are not accessible to the public. The Table 1.3 shows landslide inventories with pre and post earthquake classification and also the type of inventory regarding mapping point based polygon based inventories and also the area covered by inventories. A detailed description of each inventory is presented in chapter 6 design of the system under "current situation" section.

Table 2.3 Landslide inventories in Nepal collected during the field visit.

Landslide inventory	Number of landslides	Point/ Polygon/ polyline	Classification of type of landslides Yes/No	Area covered	References
C.D.E.S. T.U. Nepal	5003	Polygon	Yes	Nepal	(Pokharel & Bhuju 2015)
ICIMOD Koshi River Basin 1992	3559	Polygon	No	Koshi River Basin	(Zhang et al. 2016)
ICIMOD Koshi River Basin 2010	3398	Polygon	No	Koshi River Basin	(Zhang et al. 2016)
Valagussa et al. 2016	4300	Polygon	No	Gorkha earthquake 2015	(Valagussa et al. 2016)
ICIMOD	5159	Polygon	No	Gorkha earthquake 2015	(Gurung & Maharjan 2015)

BGS and Durham University	533	Point	Yes	Initial earthquake of Mw7.8	(Jordan et al. 2015)
Martha et al. 2016	15551	Polygon	Yes	Gorkha earthquake 2015	(Tapas R. Martha et al. 2016)
IMHE CAS	2645	Polygon	No	Gorkha earthquake 2015	(Zhang et al. 2016)
ITC	2513	Polygon	No	Gorkha earthquake 2015	Tanyas (unpublished data)
Durham University	2117	Polyline	No	Gorkha earthquake 2015	(Colm Jordan 2015)
MacDonald, Dettwiler and Associate (MDA)	333	Polygon	No	Initial earthquake of Mw7.8	(HDX 2015)
British Geological Survey	182	Polygon	Yes	Initial earthquake of Mw7.8	(Jordan et al. 2015)
Kargel et al. 2016	4312	Polygon	No	Gorkha earthquake 2015	(Kargel et al. 2016)
Gnyawali and Adhikari 2016	19332	Polygon	No	Gorkha earthquake 2015	(Gnyawali & Adhikari 2016)

3. STUDY AREA

The area of research lies in the southern part of Rasuwa district (Figure 1.5) along the Pasang Lahmu highway that connects Kathmandu to China and located at latitude 27° 55’ to 28° 25’ N and 85° 0 to 85° 50’ E longitudes (YONSED 2016), it is part of the Bagmati zone. The district headquarter is Dhunche. The area covered by the district is about 1544 square kilometres. Elevation in the region ranges from 667 meters to 7227 meters from MSL(Wikipedia 2017). According to the Nepal census Central Bureau of Statistics (2012), the population of the district is 43,300. The population density of the district is 28 persons per square kilometre (Central Bureau of Statistics 2012). Rasuwa is located in the northernmost part of the country bordering with China. It also has touristic attractions like Langtang national park and trekking locations such as a Gosaikunda lake (Wikipedia 2017). In Rasuwa district a total of 1135 households were affected. People were left homeless, and their sources of livelihood were also damaged. A total of 35 landslides affected the infrastructure in Rasuwa district. A total of 5 schools were affected by the earthquake, out of which three were damaged, and two were vulnerable. Also, hydropower project near Mailun Khola was severely hit by earthquake-induced rockfalls.

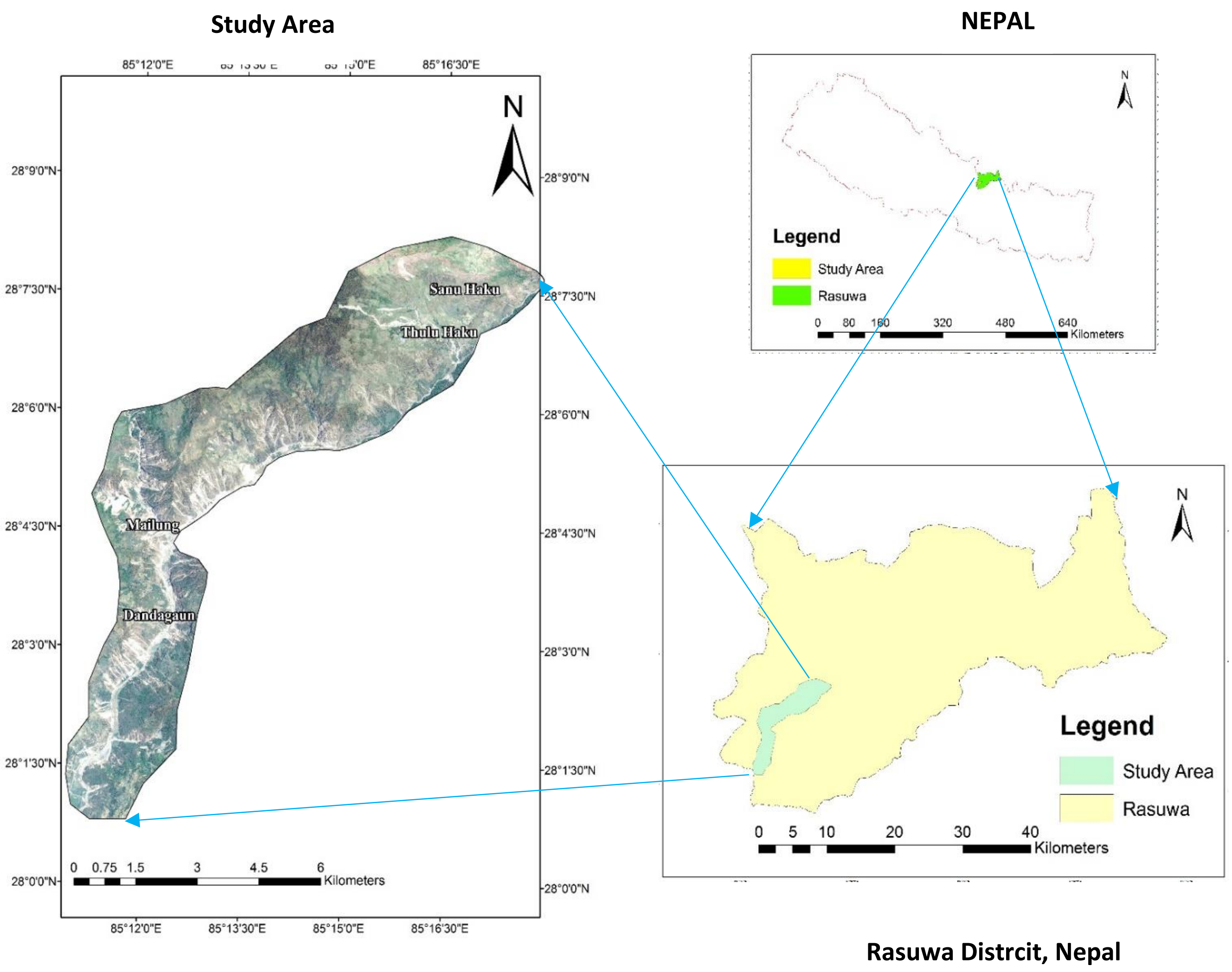


Figure 3.1 Study Area

3.1. Landuse

Land use map for the study area was created by image interpretation of GOOGLE EARTH satellite imagery before going to the field (Figure 1.6). Land use is mostly the forest, then shrubland follows by agriculture, grass and urban areas. Most of the landslides are in forest areas. However, some rockfalls occurred in built areas which resulted in the death of people in the Mailung village, Haku village. Villages like Dhandgaon and gogan have been entirely abandoned, and people are forced to live in shelters provided by NGOs and INGOs. Agriculture land in Haku VDC and Dhadgaon VDC were severely affected by the landslides occurred after the Gorkha Earthquake 2015. Landslides also dammed the river Trishuli at several locations near Gogan village landslide and caused damage to Trishuli hydropower plant projects.

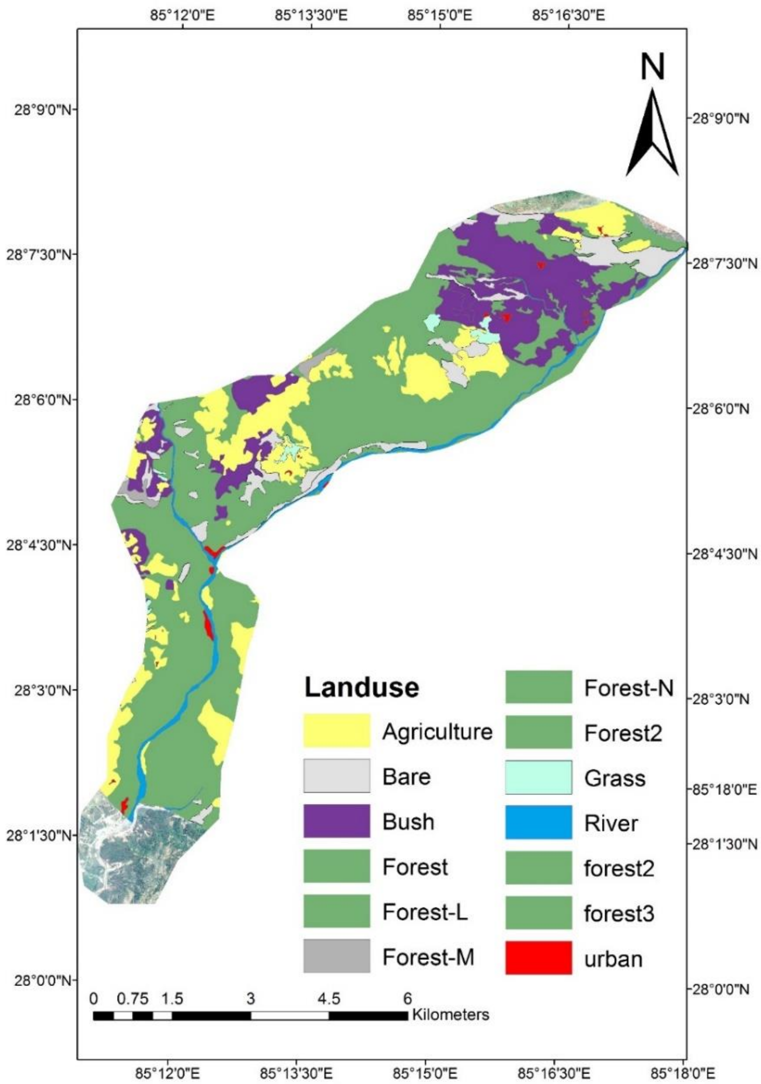


Figure 3.2 Landuse in the Study Area

3.2. Economy

According to National planning commission report on post-disaster assessment in Rasuwa Per capita Disaster Effects, NPR/person, was 179,700(NPC 2015). In the study area, most of the houses are made from wood and stones and were damaged after the Gorkha earthquake. People were left homeless, and there were many deaths after the quake in the study area. People did not get help from Government for first some days. International NGOs provided them with shelter and created many temporary shelters for the people from different villages. People also lost their cattle and livestock after the earthquake which was one of the assets for people of the region.

3.3. Climate:

Rugged terrain has an influence on the climatic condition of the area. The climate is sub-tropical and humid above 600m and cold in mid hills above 2500m(Lokendra P. Dhakal & Shrestha 2005). Orographic monsoon precipitation brings rain in the area, annual average rainfall is about 691mm, and most of it occurs during the monsoon.(YONSED, 2016). The Southern part of the Rasuwa district receives mean precipitation ranges from 19 mm to 65 mm rainfall data from 1950 to 2000 in the month of may just before the onset of monsoon season every year.

3.4. Transportation

Landslides have affected the main transport corridor between Nepal and China through RasuwaGadhi (Figure 1.7). A total of 610 meters of the road was affected by the landslides. There was damage to RasuwaGadhi bridge at Raswa Gadhi Border. The road from Galchi to RasuwaGadhi which connects Nepal to China is about 164 kilometres long road which is single lane. A road segment near Ramche to Mulkharka is about six kilometres, and it is severely affected by landslides mostly during monsoon. In November 2016 a passenger bus met accident leads to the death of 36 people.

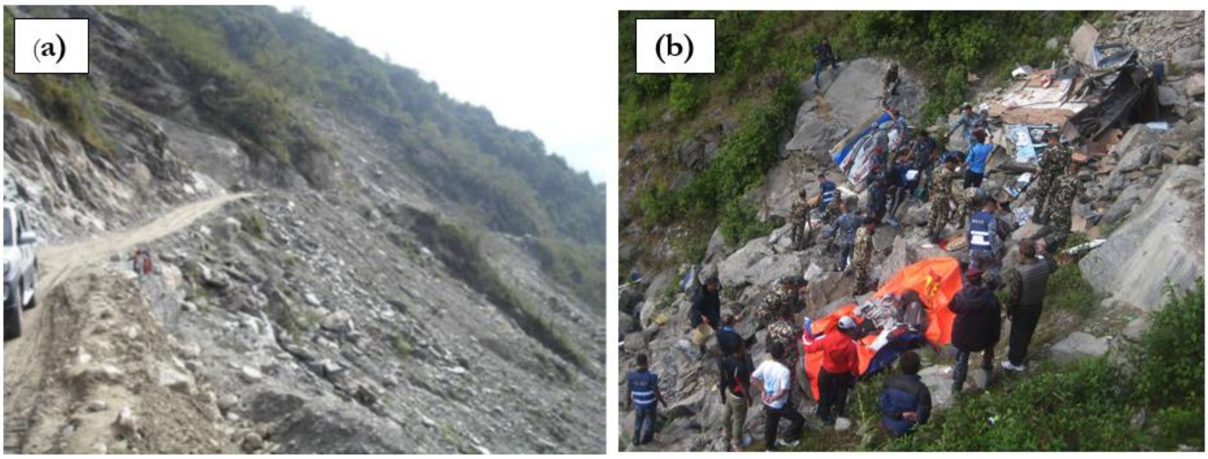


Figure 3.3 (a) Damaged road section on the way to Dhunche near Mulkharka landslide. (b) Bus accident near Ramche landslide.

3.5. Geology

Rasuwa district lies in the higher Himalayas (YONSED, 2016). This area is still rising at a rapid rate, and it leads to several deadliest earthquakes in the region. Main Central thrust (MCT) lies near the boundary of Rasuwa district. MCT is a subduction zone where the Asian plate and Indian plates collide (Searle et al. 2008). According to a study carried out by Kimothi & Juyal,(1996) near Main Central Thrust in the higher Himalayan region reflects that plate tectonics and other disturbances such as heavy rainfall can trigger landslides. Figure 3 illustrates that the fieldwork area is mostly located in the Ranimatta Formation and Ulleri Formation Dhital (2015) in the southern part of Rasuwa district.

The fieldwork area is near Dhunche headquarter of Rasuwa district and mostly along the Trishuli river which has quartzite rock and in areas near Mailung Khola Nawakot nappe is found. Lithology of the area has schist, gneiss, and other rocks (Upreti & Dhital, 1996).

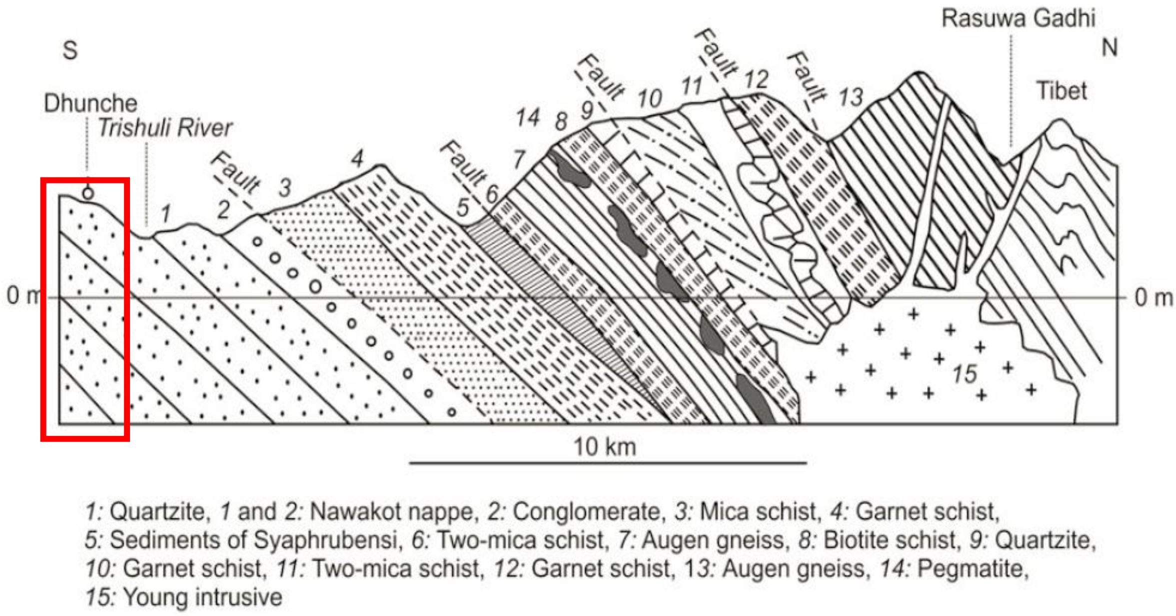


Figure 3.4 Geological section across the root zones of the Trishuli river valley in Rasuwa district Dhital (2015) red rectangle shows the study area.

4. LANDSLIDE INVENTORY TECHNIQUES:

The main purpose of this chapter is to give a detailed overview of the available landslide inventory techniques that are used in this study. It will provide indications for the use of techniques for getting data for NELIS (Nepalese landslide information system). Several landslide inventory techniques are discussed in this chapter like Visual image interpretation, UAV based, Tablet GIS-based, Involvement of local community.
Landslide mapping is performed for reporting and showing the distribution and spatial extent of the landslide occurrence in areas from local level VDC to large watersheds, and from regional to national level. Despite the significance of landslide inventories and the way that landslide maps have been prepared for a long time, there is a very poor harmonisation of criteria for creation of landslide maps and assessment of the quality of maps in Nepal.

In this study, there is an attempt made to review the landslide inventory methods that can be used for better landslide mapping by using different sources of available information and also different techniques (Guzzetti 2005). Sources of landslides information are varying in Nepal as the various organisations like (DSCWM, DMG, DOLIDAR, DWIDM) works in the field of landslides, most of the information is in analogue format in the form of reports. Selection of specialised mapping technique depends upon the purpose and the extent of the study area. There are other criteria for selection of mapping techniques discussed by Guzzetti et al. (2012) like mapping scale and spatial resolution of the available satellite imagery and most importantly skills and resources available for completing the task (van Westen et al. 2005; Guzzetti et al. 2000; Guzzetti et al. 2012). After analysing the current situation and need for harmonisation of landslide inventory techniques in Nepal, several landslides inventorying techniques have been analysed based on the availability of resources and technical advancement in the departmental organisation in Nepal government.

Table 4.1 Landslide inventory techniques that are used in this study.

No.	Inventory Techniques	Types
1.	Visual image interpretation	1. Google Earth Imagery 2. USGS Helicopter flights(Collins et al. 2015) 3. Unmanned aerial vehicle
2..	News and Media reports	Reports and newspaper(The Himalayan Times 2016)
3.	Tablet based GIS	Field based mapping(Mauro De Donatis et al. 2006)
4.	Community-Based Mapping	Interviews(DSCWM 2016)

Four inventorying landslides techniques shown in Table 4.1 can be used. In this study before going to field co-seismic landslides were mapped using Google Earth imagery. Post monsoon 2016 landslides for the study area were mapped using Google Earth imagery base map on Windows operating tablet PC and also field survey. Interviews and questionnaire with local people were one of the important sources of information about occurrence and damage caused by landslides at the VDC level. During a visit to several organisations, existing data related to landslides were collected and shown in section 2.1 on existing landslides in the literature review.

Landslide Inventory Methodology

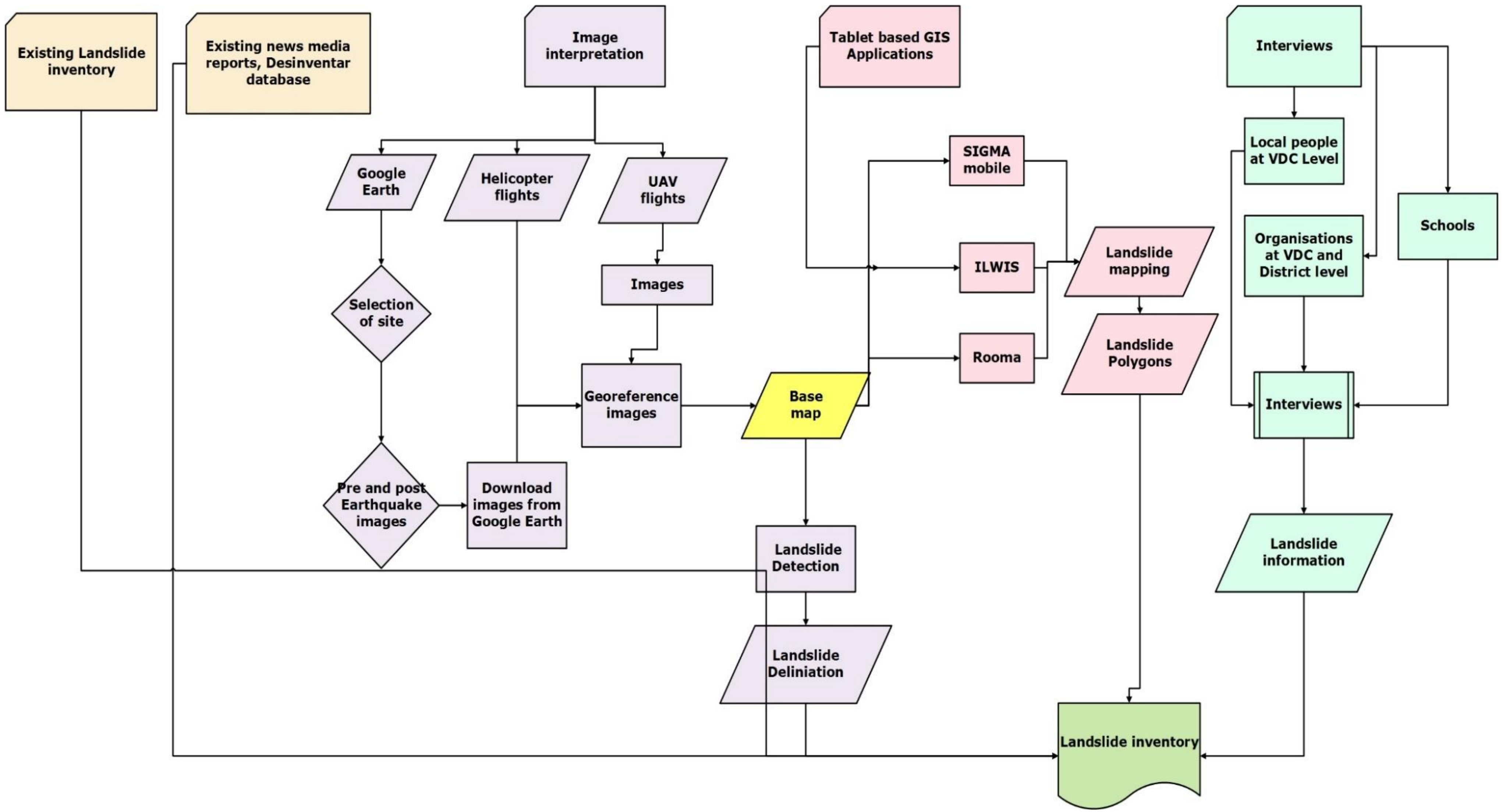


Figure 4.1 Landslide inventory techniques used in this study

4.1. Visual image interpretation:

In this section, visual image interpretation techniques used during field work are described. Visual image interpretation of GOOGLE EARTH imagery, USGS Helicopter flights,are analysed as a tool for mapping landslides.

4.1.1. Visual interpretation of optical images

GOOGLE EARTH imagery downloaded from GOOGLE EARTH PRO for the selected study area have been chosen. Then a mosaic of images was prepared, then the image was georeferenced. In this study, I mapped landslides using GOOGLE EARTH data, and spatial resolution of the imagery was around one meter which is already high resolution to carry out mapping. In figure 4.2 pre-earthquake and post-earthquake satellite imagery are shown with mapped coseismic landslides.

From satellite imagery, I was able to map 131 landslides covering a total of 4.3 km² of the study area. I mapped these landslides before going to field at that time I was learning how to map landslides, the fewer number of landslides is the result of mapping only along the Trishuli Valley.

(A)

(B)

Figure 4.2 (A) Shows Pre-earthquake image (B) Coseismic landslides mapped from GOOGLE EARTH imagery.

4.1.2. USGS Helicopter Flights:

Helicopter flights are crucial and valuable data for landslide mapping, but there are limitations to it like it is very expensive and can only be done with funding sources. Helicopter flights are mainly done after any significant event by international organisations like USGS. In Figure 4.4 photo taken from a helicopter video is shown with mapped landslides.

Collins et al. (2015)performed landslide inventory mapping using a helicopter in 12 priority areas; the flying period was five days in total that begins on May 27, 2015. Landslide researchers documented existing landslides during the flight. Collins et al. (2015) collected photos and videos of landslide affected areas.

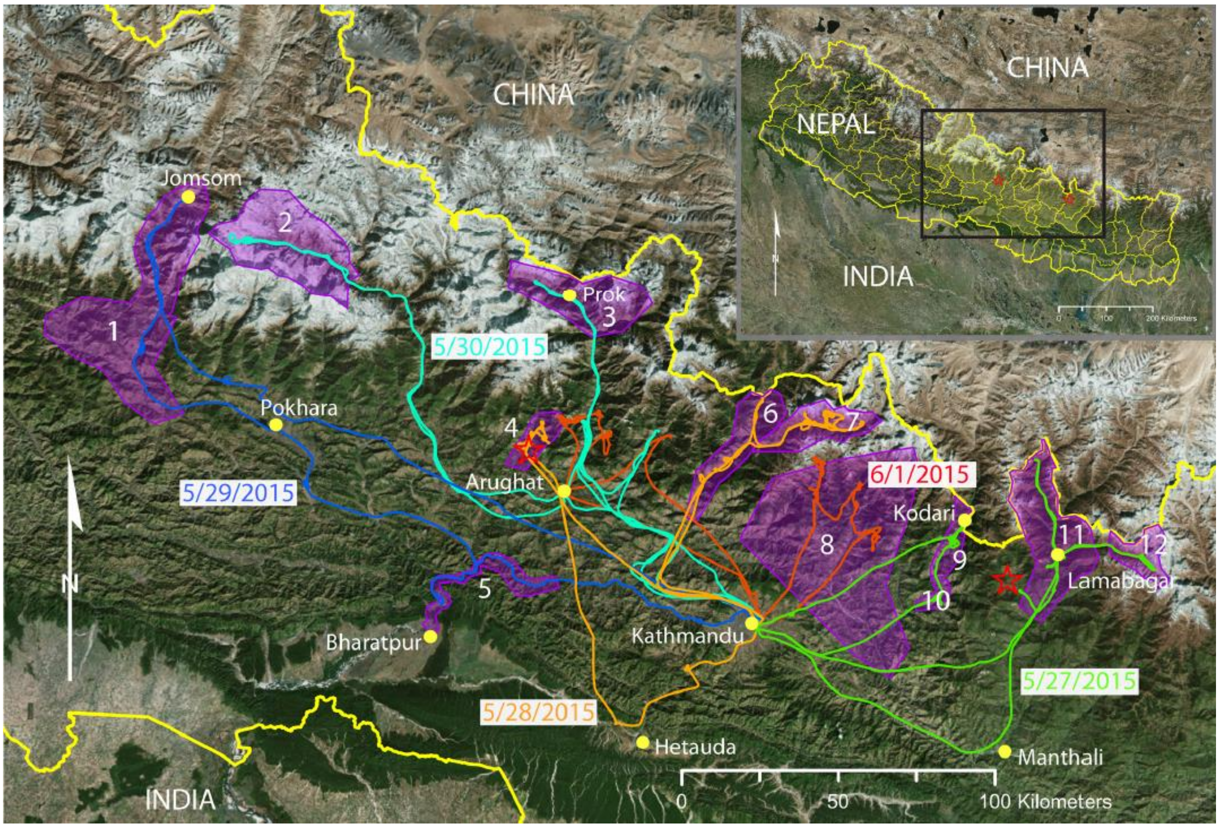


Figure 4.3 Helicopter flight path after the Gorkha earthquake landslide mapping assessment. Colour of the path refers to the date of flight.

The study area lies in southern part of rasuwa which lie under zone six and flight path of the date 28 may 2015. In zone six video footage of Langtang debris avalanche is available. In figure 4.4 I tried to map landslides directly in an image taken from helicopter video footage. The spatial extent of the debris slide is clearly visible.

Figure 4.4 Photograph is showing Langtang debris avalanche, which buried whole Langtang village.

4.2. Fieldwork Techniques

4.2.1. Unmanned aerial vehicle

In this section, I try to give an overview of conditions and limitations of using UAV at the field level. Unmanned aerial vehicles (UAV) also commonly referred as "drones" are the aerial vehicles that can be controlled remotely and can carry a wide variety of sensors, which depends upon quality and efficiency of the drone used. There are various types of UAVs available worldwide, and much more are being developed as a curiosity of people and applicability of UAV in various field of sciences are increasing. There are three common types of UAVs platforms 1) Single -rotor platforms, 2) Multi-rotor platforms, 3) Fixed wing platforms.

Landslides may block rivers or roads, and for mapping, after major landslide hazards helicopters are very expensive to operate and often needed for quick response work, but if a UAV is sent into places that are otherwise impossible to see it helps to get a close overview of the situation. A UAV can be a good extension for field mapping as it allows the mapper to quickly view locations that would be tough to access, or dangerous to access. In Nepal, during field visit, we used a UAV in the mailung rockfall affected area. We Used a Phantom 2 Vision drone to take photos and videos of the Mailung area, but it was very windy in the river valley, and we could not get proper videos, but still, we were able to get an overview of the area.

There are many limitations of using UAV in the mountainous terrain of Nepal for mapping landslide prone areas. There are windy conditions in the river valleys, and most of the landslides occur along river valleys. There were only short UAV Flights were possible in the field due to battery backup time of only 5 minutes. Another important issue is that the procedure to get the permission of using a drone in the field takes a very long time of almost one month and sometimes may be a more time-consuming process. In Nepal, it is restricted to fly UAV in national park areas, and most of our study area comes under the Langtang national park. There were many attempts to use UAV for hazard assessment in adjacent areas of Kathmandu valley but still in higher Himalayan regions where landslides are most persistent, use of UAV to map landslides is still not a very straight forward task.

Figure 4.5 Landslides mapped from UAV captured images during the field work near Mailung Khola, Rasuwa.

4.3. Tablet based GIS

In this section, I describe the tablet PC application used for mapping landslides in the field. I used three applications one windows based ArcGIS, and another two application were Android operating system based.

During fieldwork, I used a Lenovo Windows operating tablet and one Acer Android operating tablet to carry out mapping of landslides after the monsoon. Before going to the field, we prepared base maps from Google Earth, and then I mapped coseismic landslides in ArcGIS and transferred the content to tablet PC. During field, I was able to access coseismic landslides and overlay these with a base map. I digitised landslides that were either extended or entirely new. There were several issues regarding the use of tablet PC in the field like readability on screen was difficult. Sometimes it was almost not visible in abundant sunlight. However, it was ok when I used it in shades. Digitising using specialised stylus saved much time, and it is an essential tool if you are using low-end tablet PC. I mapped a total number of 97 landslides in the field and about 307 landslides before going to the field. There were about 166 landslides that were overlapped between two datasets. Many small landslides merge to form bigger landslides as the result of erosion process due to monsoon rains. In Figure 4.6 A) there is a clear indication of extension of landslides after monsoon 2016 and some new landslides were also triggered. Apart from mapping landslides in the field, I tested applications listed in Table 4.2 to see the usability and limitation of application for landslide studies.

(Rapid Offline Online Mapping Application) by a PhD from Lausanne University is an android based application, and there are several limitations of it listed in Table 4.2 The main limitation is that user himself cannot load the required basemap but he has to ask the author to put the base map onto it, so it is tough to get the basic base map uploaded to the application by the author every time.

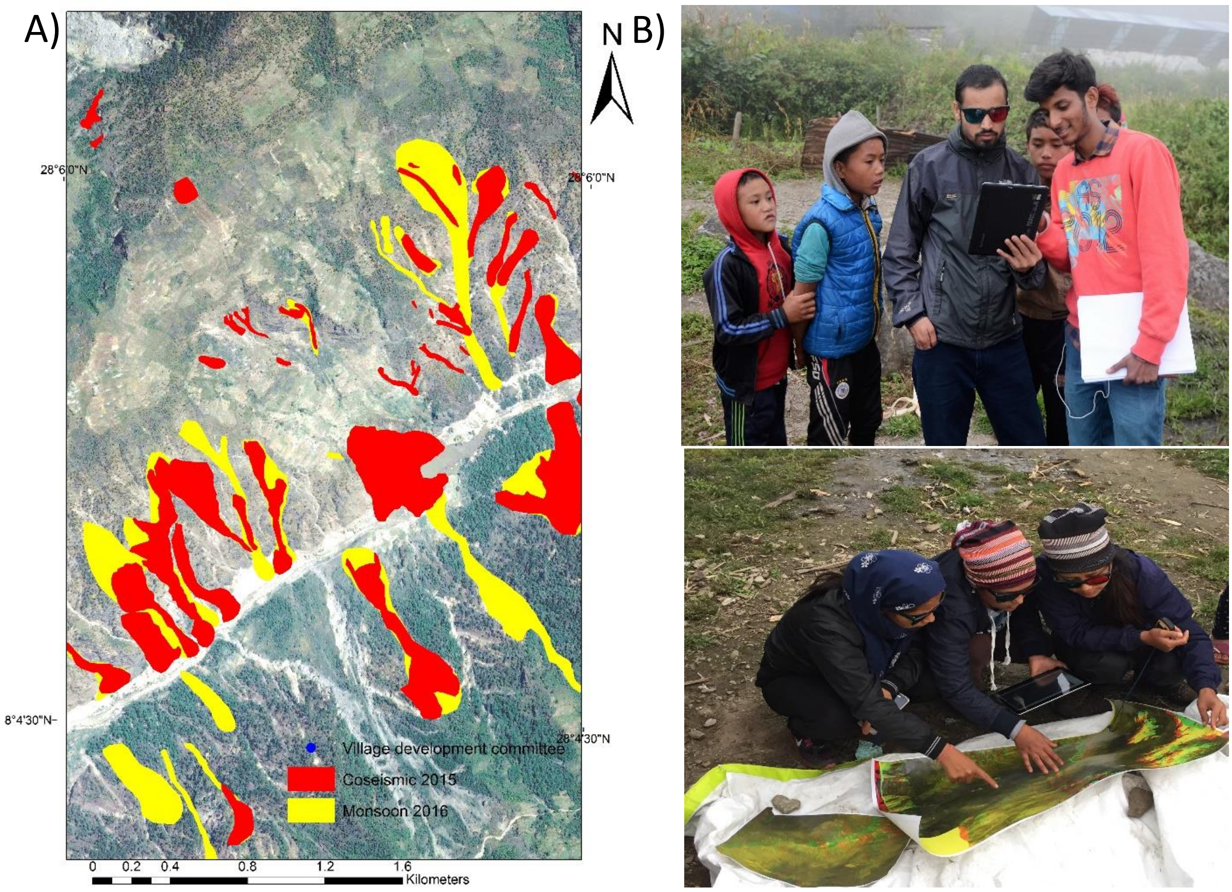


Figure 4.6 A) Showing extension of landslides after monsoon 2016 mapped using tablet PC in field B) Local people and student from Tribhuvan University testing the Tablet PC applications

Another application was used from ICIMOD it is called as Disaster reporting application, it was developed during the response phase just after the Gorkha earthquake, and it has many useful inputs like user can upload the picture of the event and look for nearby hospitals, shelters. The main limitation of this application is that user has to register himself before using the application to the ICIMOD server then only it is possible to report any hazard related information. Once uploaded then the user cannot see the uploaded data, it is directly sent to ICIMOD internal server.

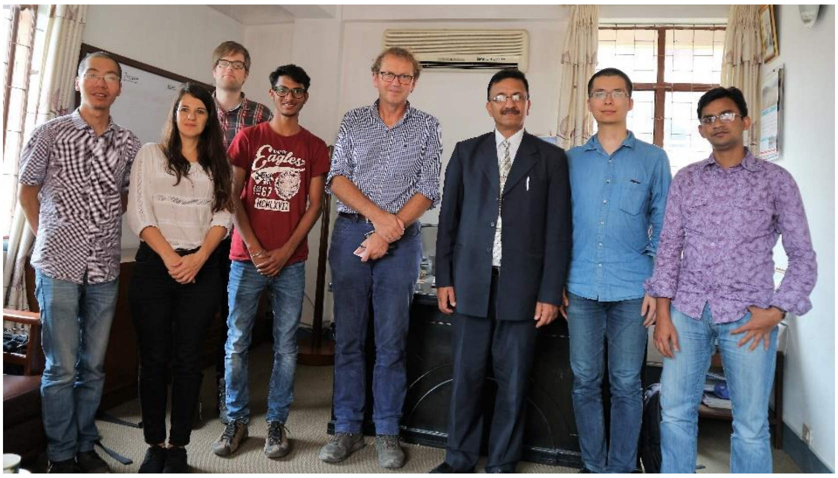
Table 4.2 Showing Different Tablet PC applications that are used during fieldwork.

1. ArcGIS:	*2. Disaster reporting (ICIMOD)*	*3. (Rapid Offline Online Mapping Application)*
Advantages: 1. Landslides mapped in the field after monsoon using ArcGIS. 2. It is a specialised tool to map landslides and visualise the result. 3. Can be operated without the internet if the user has a license.	Advantages: 1. It can be very good tool for Hazard reporting in urban cities. 2. It has geocoded information And, users can upload the Photos of the situation. 3. It shows 15 basic infrastructures Near the person operating the App.	Advantages: 1. It is an offline application. 2. It can be used on field to map landslides if the user has base map of the area. 3. After collecting data on field user can upload data to online database.
Disadvantages: 1. It is an expensive software, but people can use open source QGIS. 2. Requires Windows operating tablet PC to operate it. 3. 3.Requires specialised rugged tablets to run Arc GIS on the field.	Disadvantages: 1. First user should register an account at ICIMOD server, then only can report hazards. 2. It is an online application hence, cannot be operated in remote areas. 3. After reporting users cannot see what they have reported.	Disadvantages: 1. User cannot upload required imagery to the application. 2. Only developer of the Application can upload the base maps 3. Digitizing is not user friendly on android tablet pc with hand. 4.

4.3.1. Meeting with organisations like DSCWM, DMG and other organisations

During field work, several organisations were visited, and information and data related to landslides were collected. A total of three field-based reports were collected which gives much information about landslides in the study area. Along with reports these organisations also maintains the GIS data which can be the input to the NELIS (Nepalese Landslide Information System). These reports can facilitate information about landslide occurrence and damage caused by landslides

Workshop on landslide management in Nepal October 2016



Visit to DSCWM Kathmandu

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Figure 4.7 Visit to several organisations during fieldwork.

4.3.1.1. Department of Mines of geology

Field based geological assessment of settlements affected after the quake was carried out by the Department of Mines and Geology in Rasuwa district. A report is available from the DMG which was completed in July 2016. The main objectives of carrying out assessment were to categorise the affected settlements into safer villages, unsafe villages and recommendation for temporary relocation sites. For carrying out, this assessment two methodologies were adopted desk study and onsite investigation. The report is based on 15 days of on field surveys and also visual inspection of the earthquake affected villages. The report consists of information related to geological, geomorphological, geotechnical and social parameters. They have covered the Haku Besi, Sanu Haku, Thulu Haku, Gogan, Thulugaun, and Dhandgaon villages in the assessment.

The general structure of the assessment deals with the general description of the area, its location, damage. Then information related to topography and land use is provided for each village follows with geology and geological hazards affecting the village.
They provided a table for each chapter that consists of information about dip direction, discontinuities in the area, orientation and rock type or soil type. An example from the report is given in Table 4.3. They also provided detailed information about geological hazards in the area like information related to rockfall zone that is about 600 meters away fro the village that can cause severe damage in future. They are also debris slide just along the village that might expand in the future which leads to damage to the village shown in figure 1.9.

Table 4.3 Geological assessment sheet for Sanu Haku village, Rasuwa.

Village	Hill slope(dip direction/ dip amount)	Discontinuities	Orientation (dip direction/ dip amount)	Rock type/Soil type
Sano haku, Joints measured at 537	165/25	Foliation	330/50	Garnetiferous schist
			325/20	
		Joint set 1	295/90	
		Joint set 2	215/90	
		Joint set 3	355/8	

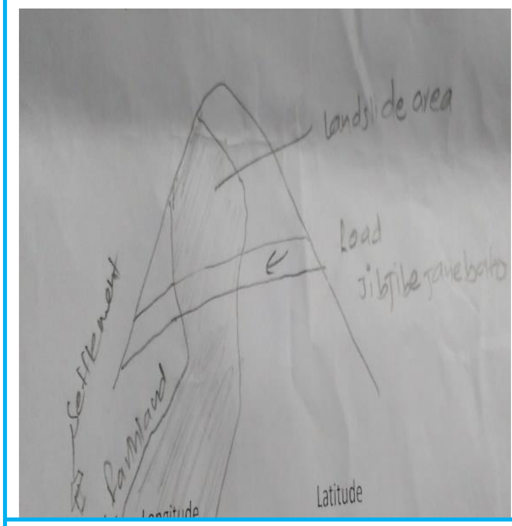
Figure 4.8 Geological hazards next to Sanu Haku village in Rasuwa image source: (Facebook page Acharya Akash)

4.3.1.2. Department of soil conservation and watershed management (DSCWM)

Another field-based mapping sheet was used by Department of soil conservation and watershed management. They did landslide area mapping of lower phalakhu Khola sub-watershed of Rasuwa District. The overall objective of the study was the mapping of landslides in the region. The specific objective was to identify the landslides and to prepare a database of the landslides. The methodology adopted in the study are coordinating meeting, consulting meeting, Preparation of datasheet, orientation to field surveyors and field assistants, field visit. They also showed spatial location of landslides on GIS platform. However, most of the GIS data are most available for public and can only be accessed through reports.

Table 4.4 An example of the landslide mapping sheet used for study by DSCWM

District: Rasuwa VDC: Bhorle	Ward: 1 and 4	Village/Tole: GhatteKhola	
1. Dimension of Landslide : Length: 1000m	Width: 50m		
2. Position on Hill: Hill top /**Middle** / Toe			
3. Land Crakes –	- Length	- Width	
4. Impacted area: 4000m2			
5. Possible impact area: 800m2			
6. Property in possible impact area:	a. Farmland: 40 ropani	b. Settlement: 3	
c. Road: 50m	d. Irrigation canal --------m		
e. Other property: -			
7. GPS points:	Longitude	Latitude	Elevation
	0622270	3098462	1608m
8. Sketch Map of Landslide			



9. Photo of the side Digital: 5929,7597
10. Information collected By Rajesh Chataut
11. Local Reference Person: Dinesh Ghale
12. Address: Ghalegaun
13. Phone no: 9810209972

The study was completed by mobilising energetic forest/watershed-based experts/technicians. The date sheets provide the baseline information of the landslides of particular VDCs in the Lower Phalakhu Khola watershed, which can be used for assessing landslide in future for sustainable sub-watershed planning. Efforts of DSWM officers for mapping the landslides at the sub-VDCs level are commendable; the practice as such should be applied in all other districts under DSCWM.

After studying the landslides in five VDCs, several recommendations were given by DSWM.

- To carry out a detailed study of the mapped landslides of the VDCs for better mitigation measures to be applied.
- To develop the sustainable treatment plan for the landslide mapped in the region.
- To apply the practice of mapping landslides in all the districts under DSCWM.

4.3.1.3. Mountain Risk Engineering Unit, Tribhuvan University

The field-based study was carried out by Mountain Risk Engineering unit, Tribhuvan Universty under the supervision of Professor Dhital. A report was prepared and submitted to UNDP Nepal named Landslide Identification and Hazard Assessment in Earthquake-Affected Districts. In this report, our study area was also covered and discussed. They made field based studies and also mapped landslides on GIS platform. GIS data was not accessible, but we managed to get the report from Professor Dhital. Report on damage caused by landslides as well as mapping of landslides was completed. In figure 4.9 (a) severity of the rockfall zone in the Mailung Khola is illustrated. They give a description of the landslide size, type and extent of affected area due to the landslides. Many rockfalls damaged the hydropower plant and the office near the Mailung Khola region. Figure 4.9 (a) shows the rockfall that restricted the construction of the ongoing hydropower project at the Trishuli River- The classification of landslides was carried out and mapped in GIS platform (Figure 4.9 (b)); they classified the landslides into Rockfall, Rockslide, soil slide and debris runout.

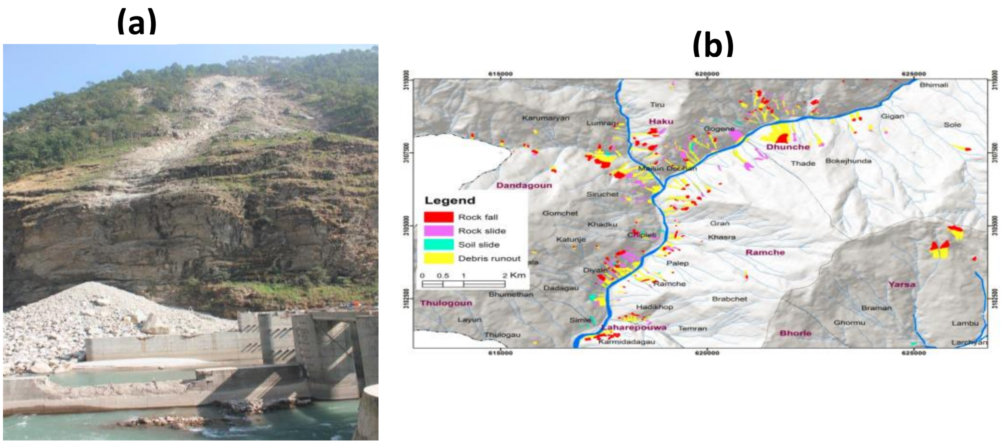


Figure 4.9 (a) About 150 meters high rockslide caused damage to the Mailung Khola Hydropower plant. (b) Landslides mapped in GIS platform for the Mailung Khola region.

4.4. News reports and old Registers

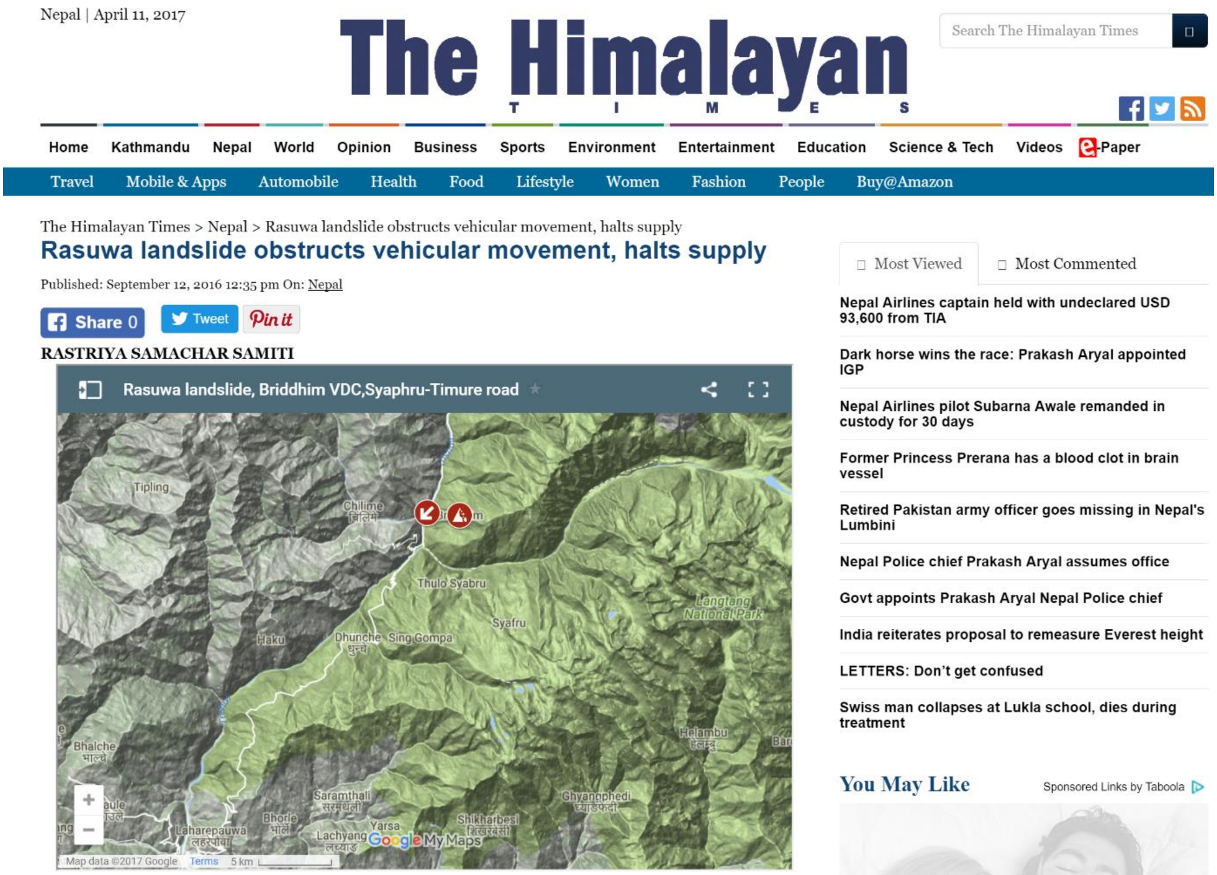
Newspaper and media reports are one of the important sources of landslide information all over the world. News article may be the first way by which people hears that a hazard has happened at the place. In Nepal landslides that occur near-road network or near the built-up area are sometimes covered by the newspaper and media agencies. Newspaper archives can give information about the damage caused by a landslide and most probable landslide location like nearest locality or village. Sometimes there are photos of the event given in newspaper that could give the spatial extent of the landslide. In today's digital era some newspaper in Nepal are also available in digital format online which enables users to find news from the past. There are newspapers like The Himalayan Times which is the most popular newspaper in Nepal sometimes covers landslides that affect the populated area or blocks river.

The Himalayan times also provides its readers with a contact address if someone needs news from particular time then they could send them an email to archives@thehimalayantimes.com. The newspaper helps anyone who wants to get information for defined dates; this is very much a step forward in making use of newspaper archives for landslide mapping.

There is a clear bias in newspaper and media reports as a proxy for information about landslides in Nepal, there could be an overemphasis of human impact, and underreporting during small events due to increased media interests during larger events and scientific correctness of the information. The table gives the previous landslide events in Rasuwa district available in archives of Himalayan times newspaper. Figure 4.10shows the geocoded information about location and damage caused by a landslide near Rasuwa Gadhi in Rasuwa district. Landslide information can be transferred to NELIS (Nepalese Landslide Information System) by experts.

Table 4.5 Shows landslide information gathered from newspaper archives.

No.	Date	Location	Damage
1.	11 -09-2016	Ramche	Landslide blocked the pasang Lahmu highway
2.	10-03-2016	Mailung road section	Human skeleton was found from the debris
3.	04-11-2016	Ramche	36 people were killed due to en route of passenger bus
4.	14-06 2015	Syaphrubeshi	Blocked the pasang Lahmu highway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Rasuwa landslide obstructs vehicular movement, halts supply

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Figure 4.10 Showing The Himalayan Times newspaper with GIS platform that shows the location of landslide and obstructed road segment.

Historical landslides information can be gathered from historical reports and road clearance registers from Department of Local Infrastructure Development and Agriculture Roads, (Dolidar). Dolidar is responsible for rural road management and development in Nepal, and most of the landslides occur near the road cuts. We visited the office of Dolidar at Trishuli Bazaar and had met with the chief engineer at the district level.WeI asked him if their department has landslide inventory, but he told me that they do not do landslide inventories and neither they keep a record of landslides, but they do maintain the road clearance reports that could give clues to the probable location of the mainly ancient landslides. Old registers of road clearance reports are very hard to get for people outside Nepal, hence make it tough to study the use of road clearance reports as a source of landslide mapping in Nepal.

4.5. Community-Based Reporting of Landslides

Involvement of local people in landslide mapping gives valuable information about the historical as well as recent landslides in the area. During fieldwork, we visited several villages like Mailung, Thulu Haku, Sanu Haku and stayed there overnight. During our stay, we talked to several people from the village like village head, school teachers, and importantly youth who knows their surroundings other than anybody else in the village.

4.5.1. Local people

We arranged a meeting with the head of the Thulu Haku village, and other important people of the village were also invited like a teacher of the primary school. There were seven masters students from Environmental Department of Tribhuvan University with us along with a lecturer; they helped us to communicate with local people. We asked residents about what has happened during the earthquake and what hazards followed after the quake. Some older people had their own stories about historical earthquakes and landslides (Pairo in Nepalese) that have happened near their surroundings. Older people were more worried about earthquake than landslides in their surroundings as they know potential failures in the region and if they are safe or not. The 2015 Gorkha earthquake caused a lot more damage in the village than any other previous hazards. Younger boys had knowledge about recent ground failure and cracks in their surroundings and when we showed them our base maps that we prepared before going to field they were able to recognise their village, Dhunche the nearest town or district headquarters and other physical features on the map. Boys even pointed out the location of new ground cracks just above the village and other cracks near the old existing landslides. We asked the opinion of the people if government provide them with the opportunity to live in another place and give you shelter than there were mixed answers from people. Some old people just wanted to stay in the place where they were born and did not want to leave their ancestral property, but younger generation had a different mindset to leave the village if they could get a better place to live and off course livelihood. In Haku village, we also encountered a policeman, and he was from a southern part of Nepal near the Indian border, so he was very enthusiastic to talk to me in Hindi and gave me useful information about how reporting of events or bad situation given to police by the people. I asked him about Gorkha earthquake event and landslides that followed after it. He told me that there are two landslides both the sides of village Sanu Haku showed in Figure 4.11 A) were triggered by the earthquake but recently in September 2016 after monsoon they both got extended and they are just 100 meters far from the village Sanu Haku. He also told me about the death of an old lady and children each in Thulu Haku and Sanu Haku after the earthquake; police maintain a record of how many people were died in during the quake and even after any other hazards. Our team stayed in Thulu Haku overnight and then we travelled to Sanu Haku and then to District Headquarter to our Hotel.

Then next we went to Mailung Village where Trishuli river and Mailung Khola meets. We went there to map landslides, and other team members were focussing on their own tasks. This time we were accompanied by a student from Tribhuvan University Mr Akash Acharya who helped us to communicate with local people and especially the person named Panche Tamang who lives alone with his family near the hydropower plant project on Trishuli river. We communicated with that person and asked him about what happened after the earthquake; he told me that during night time they heard the sound of rocks falling and in the morning everything was devastated. There were about 45 people died in one Korean hydropower plant camp, and about 30 people were killed in Chinese camp after the quake. The photos of damaged camps and surroundings are shown in the Figure 4.11 B). We asked him why he is living alone in Mailung village as village was cut from the main town for almost 18 months and they had to walk for 8 kilometers to get their basic needs from nearest town, then he told me that his four generations were living in the same place and he don't want to leave that land. We stayed at his place for the night, and in the early morning, he went with us to show more landslides in Upper Trishuli Valley. He explained what happened to these landslides and when did they happen. Before we went to Mailung Panche was helping Korean people with their hydropower plant project, and he used to show them surroundings, so he was enthusiastic in showing us cracks and failures whatever he knew about the surrounding region.

During our visit to Nepal, we were almost 15 days in the rural villages, and we encountered many villagers on the way to Dhunche from Trishuli Bazar and interviewed them about their experience about the earthquake and landslides. Most of the people were aware of past landslides like Ramche, Thade and Mulkhelker, they knew the consequences of landslides and debris flow, and they also had their way of controlling them like making walls using wooden sticks and piled them together, and also they had their indigenous vegetation species to control the slope failures. People were using old traditional methods to control the slope failures within their reach. So, it was a good experience with local people and interact with them in some way or another because at some places people could understand Hindi and it was good for me to get more answers from them regarding earthquake and landslides in their surroundings. Local People are the most valuable source of information if you want to study their surroundings in detail and examine possible happenings just after the event

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Figure 4.11 Showing A) Landslide near Tulu Haku and Sanu Haku villages B) Damage caused by rockfall near mailing village.

4.5.2. Schools:

We visited the school at Dhunche District headquarters, it is a senior secondary education school, and students came from nearby VDCs, and teachers stay at Dhunche and surrounding villages. We visited the school just after the festival of Dasai; it was not possible for us during first three weeks of stay in Nepal to talk to school children and teachers because of holidays. Finally, we managed to get an appointment with

The school principal, and he showed us school rooms and communicated with the kids. We asked them to test tablet PC applications for reporting of landslides, the install the Android application onto their phone and tried the application. The school has good infrastructure like computers, printers and wireless internet, only available to teachers and administrative staff. We asked school teachers that if they could organise meetings with the students and their parents to discuss any hazards in their surroundings, then head of the school told that if education department includes this into their curriculum, then they could do it. Otherwise, they do not have time as they have different things to do.
In Haku village also there was a school teacher, and she told us that most of the teachers uses social media and have to access the internet. They also teach Disaster Management in the school and included Maharo Langtang (Surroundings of Langtang) it is a textbook about disaster management in their school curriculum. Students are well aware of the disasters happening in their surroundings. Occasionally Department of Soil and Watershed Management and Officers from Langtang National park arrange meetings with students and teach them about landslides, earthquakes and safety precautions to take during those time. We showed maps to students and ask them to recognise their school buildings and other things on map, and they were able to point it out on the map, so if there is any reporting system that uses Google Earth in background then students can show it on map viewer, and teacher can help them to do it more efficiently and then teachers can finally send data to responsible department at district level. For carrying out the reporting of landslides teachers and other staff needed to be trained then they could contribute to the system.

Figure 4.12 A) Meeting with village head and school teacher at Thulu Haku B) School in Dhunche.

5. ANALYSIS OF LANDSLIDE INVENTORIES TRIGGERED BY THE GORKHA EARTHQUAKE

5.1. Data used in analysis

Landslide inventories can be classified into two categories: Historical landslide inventories (Malamud et al. 2004a) and event-specific landslide inventories associated with triggering events e.g. rainfall events and earthquakes (Valagussa et al. 2016). In this study, event-specific inventories from the 2015 Gorkha earthquake are used to analyse the frequency-area distribution of landslides in the study area and also for the entire earthquake affected area. The analysis is performed using five different inventories prepared after the 2015 Gorkha event by various research groups around the world. Landslide inventory data were collected during fieldwork in Nepal by contacting institutes that are researching landslide triggered by the Gorkha earthquake. Data used in the analysis are shown in Table 5.1 along with information related to the number of landslides mapped in each inventory and aerial extent of the inventories.

Figure 5.2. Shows Six landslide inventories related to Gorkha earthquake, and there is a variation in some landslides for the same event. Inventory that was generated by Durham University was readily available through the online portal of the Nepal earthquake response https://data.humdata.org/group/nepal-earthquake (HDX 2015), but for other inventories shown in Table 5.1 authors were contacted to get the data. Most landslides inventories are represented by polygons and hence enable statistical analysis about their areas (Malamud et al. 2004a). There are point based inventories for co-seismic landslides by ICIMOD generated by Gurung & Maharjan (2015), and Tribhuvan University (Gnyawali & Adhikari 2016). There is also one inventory based on polyline by BGS (Jordan et al. 2015) and Durham University. In this study, an attempt is made to analyse the area frequency distribution and the differences between the inventories (matches and mismatches). Detailed description landslides inventories used is given in Table 5.1.

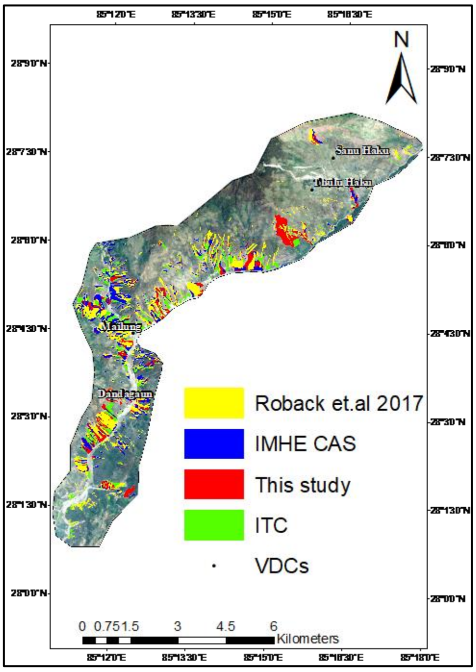


Figure 5.4 Showing landslide inventories used for analysis from cropped common area

Table 5.1 Landslide inventory used in the analysis

No.	Landslide inventory	Number of landslides	Domain of the study area	Differentiation of scarp and Body of landslide	Mapping source	Point/ Polygon/ polyline	Classification of type of landslides Yes/No	Figure	References
1.	IMHE CAS	2645	No	No		Polygon	No	Figure 5.2 (a)	(Zhang et al. 2016)
2.	ITC	2513	Yes	No	GOOGLE EARTH Imagery	Polygon	No	Figure 5.2 (b)	(Tanyas Unpublished dataset)
3.	Roback et.al 2017	24915	Yes	Yes	DigitalGlobe Worldview-2 and -3 imagery	Polygon	No	Figure 5.2 (c)	(Roback et al. 2017)
4.	Durham University	2117	No	No		Polyline	No	Figure 5.2 (d)	(Colm Jordan 2015)
5.	(Kargel et al. 2016)	4312	Yes	No	GOOGLE EARTH Imagery	Point	No	Figure 5.2 (e)	(Kargel et al. 2016)
6.	(Gnyawali & Adhikari 2016)	17532	Yes	No	GOOGLE EARTH Imagery	Point	No	Figure 5.2 (f)	(Gnyawali & Adhikari 2016)
7.	This study (Coseismic Gorkha)	131	Yes	No	GOOGLE EARTH Imagery	Polygon	Yes	Figure 5.1	

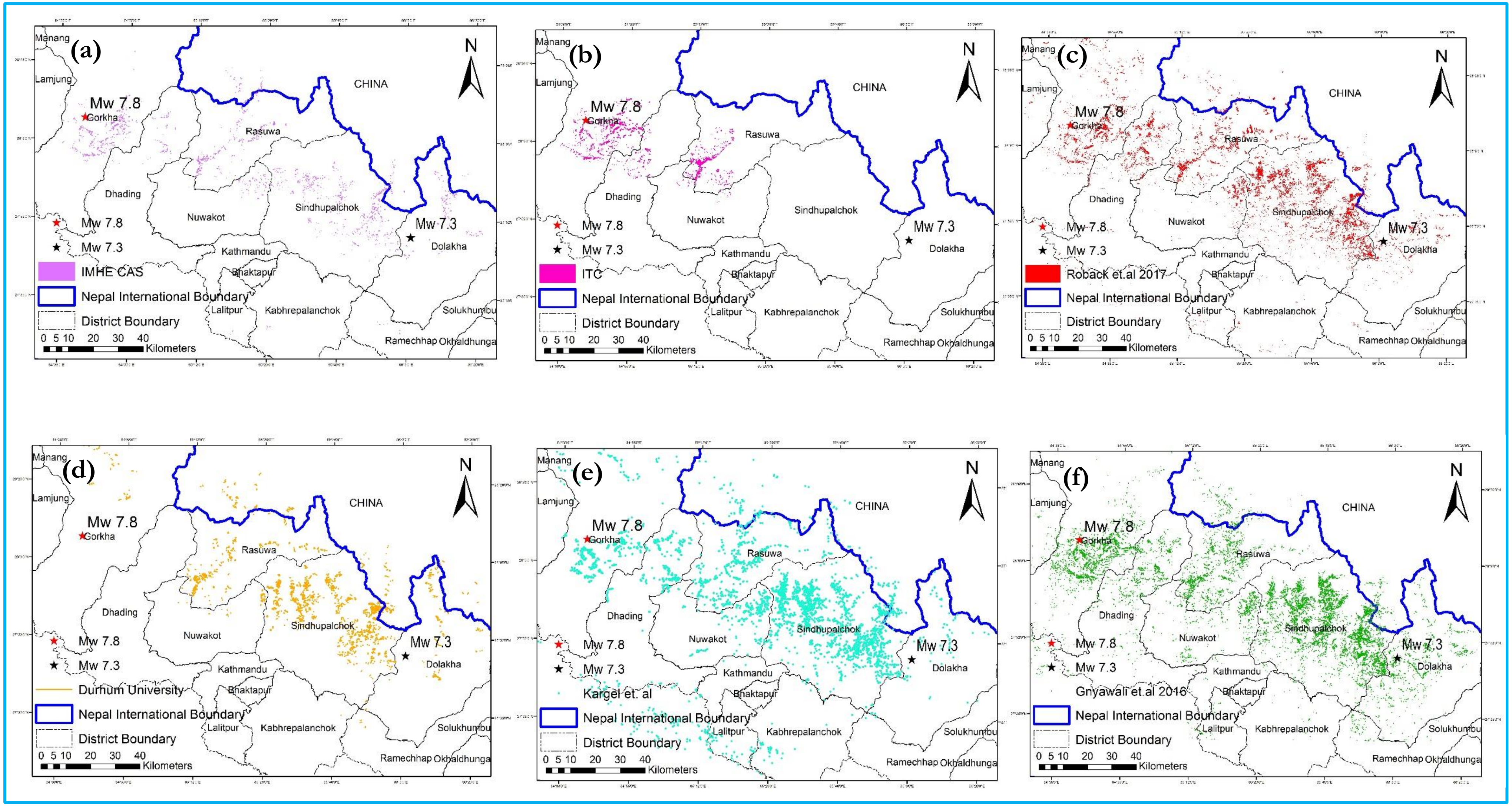


Figure 5.5 *Showing landslide inventories used for analysis from Gorkha event.*

5.2. Comparison of the landslide spatial distribution

For the comparison of three inventories available for the particular study area in Rasuwa as illustrated in figure.5.3, an attempt is made to determine the cartographic matching and mismatching among three different landslide inventories for the commonly mapped region.

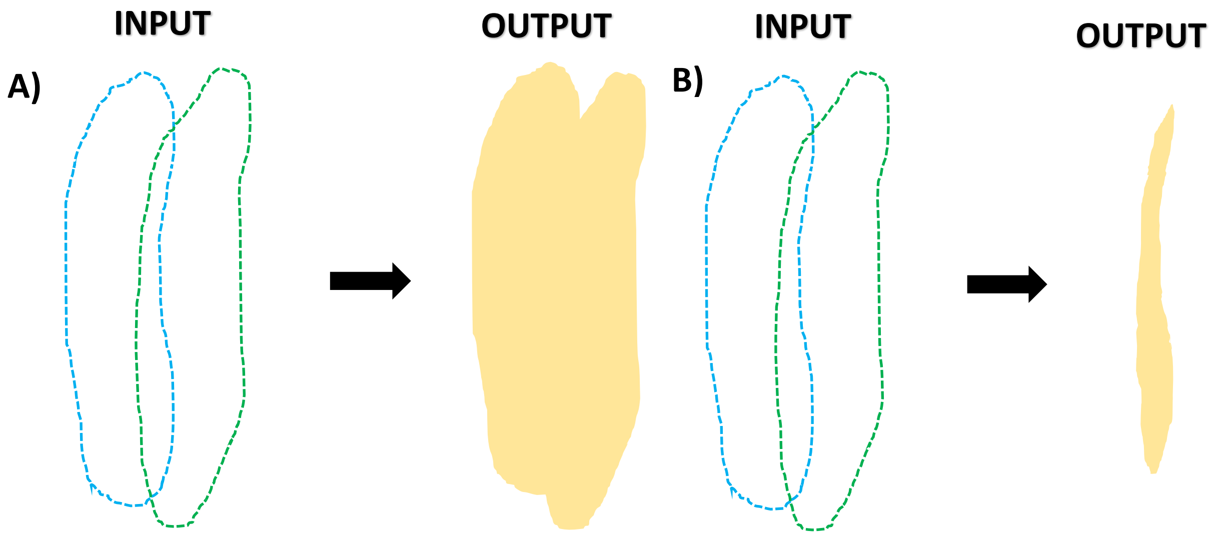


Figure 5.3 A) Example of Union with features within a feature class that overlaps ESRI (2017b) *B) Example of Intersect with a feature within a feature class that overlaps*(ESRI 2017a).

Carrara et al. (1992) provided an method to evaluate degree of match and mismatch between two inventory maps. The mismatch index, E, is given by:

$$E = \frac{(A_1 \cup A_2) - (A_1 \cap A_2)}{(A_1 \cup A_2)},\ 0 \leq E \leq 1 \qquad \text{(Equation 5.1)}$$

$$M = 1 - E, 0 \leq M \leq 1 \qquad \text{(Equation 5.2)}$$

Here, E is the mismatch and M is the matching between the inventories.

Union and intersection described in figure 5.3 are used in equation 5.1 to get matching and mismatch between the inventories.

Table 5.2 Statistics for the three landslide inventory maps for the Study Area

		IMHE CAS	This study	ITC
Total number of mapped landslides	Number	338	131	197
Total mapped landslide area	km²	2.94	4.2	5.04
Percent of landslide area out of Total Study Area	%	3.37	4.85	5.77
Smallest mapped landslide	m²	112.23	121.19	95.49
Largest mapped landslide	m²	151708 .91	341901.4 9	764038.11 8

Table 5.3: Comparison of landslide inventory maps in the study area. Mapping Error or matching (E), and mapping mismatch (M), computed using equations (5.2) and (5.3), respectively. Interpretor A, (IMHE CAS). Interpreter B, (This study). Interpreter C, (ITC).

	Area m²	Percentage of area covered regarding total study area
Landslide area Mapped by Interpreter A	2940746.33	3.37 %
Landslide area Mapped by Interpreter B	4233903.44	4.85 %
Map Interpreter A ∪ Map Interpreter B	5055386.77	6.74 %
Map Interpreter A ∩ Map Interpreter B	2122932.49	2.83 %
Mapping Error, E		0.580
Mapping match, M		0.420
Landslide area Mapped by Interpreter A	2940746.33	3.37 %
Landslide area Mapped by Interpreter C	5043072.67	5.77 %
Map Interpreter A ∪ Map Interpreter C	6005657.33	8.01 %
Map Interpreter A ∩ Map Interpreter C	1960725.06	2.61 %
Mapping Error, E		0.67
Mapping match, M		0.33
Landslide area Mapped by Interpreter B	4233903.44	4.85 %
Landslide area Mapped by Interpreter C	5043072.67	5.77 %
Map Interpreter B ∪ Map Interpreter C	6533826.26	8.71 %
Map Interpreter B ∩ Map Interpreter C	2764641.80	3.69 %
Mapping Error, E		0.577
Mapping match, M		0.423

Results are summarised in Table 5.3. Mapping error ranges from 0.57 to 0.67 and matching in the inventories ranges from 0.33 to 0.42. Largest landslide area mapped that is 5.77% of the total study area is by ITC among other three inventories that are the result of mapping large landslides by combining smaller landslides. The smallest area mapped by IMHE CAS that is 3.7% of the total study area.

Above discussed mismatch and matching in mapping of inventories is the result of these factors

- Differentiation or elimination of pre-earthquake and coseismic landslides during the mapping process.
- The spatial resolution of the satellite imagery used can results in massive landslides if the resolution is coarse and it affects the total mapped landslides regarding the number and total area.
- Amalgamation of smaller landslides into bigger landslides is the result of personal preference of the author and also the purpose of the inventory.
- The purpose of the landslide inventory (for e.g. For getting an overview of landslide hazard one will just map landslides superficially on the other hand for detailed hazard assessment mapping of landslides in detail is needed.

5.2.1. Effect of amalgamation in landslide inventories

Amalgamation is the mapping of nearby smaller landslides as a single polygon; it may lead to possibly severe distortion of the statistical analysis of these inventories (Marc & Hovius, 2015). In some regions, landsliding can be very condensed, and several contiguous landslides may join runout areas. Amalgamation is often due to errors resulting from lack of expertise of the interpreter. It may also happen when landslide inventory mapping is carried out using (semi)-automated classification and change detection based on optical satellite images e.g. (Martha et al. 2010).

In Figure 5.4 landslides near Mailung village as mapped by four different people are presented. It shows that the number of mapped landslides for the same area differs per person who depends upon the personal perspective in mapping and method of mapping adopted. Tanyas(Unpublished dataset) Figure 5.4 (B) and this study Figure 5.4 (C) mapped landslides using Google Earth imagery and mapped 25 and 43 landslides respectively. In figure 5.4 (A) IMHE CAS mapped 65 landslides for the same common area using GOOGLE EARTH satellite imagery. In Figure 5.4 (D) shows the 102 landslides mapped by Roback et al. (2017) which is the result of using high-resolution DigitalGlobe Worldview three satellite imagery by the author. The difference in the number of mapped landslides is the result of personal mapping preference of the authors and also the detail of delineating landslides. Later in section 5.3 quality and completeness of the inventories are discussed in more detail

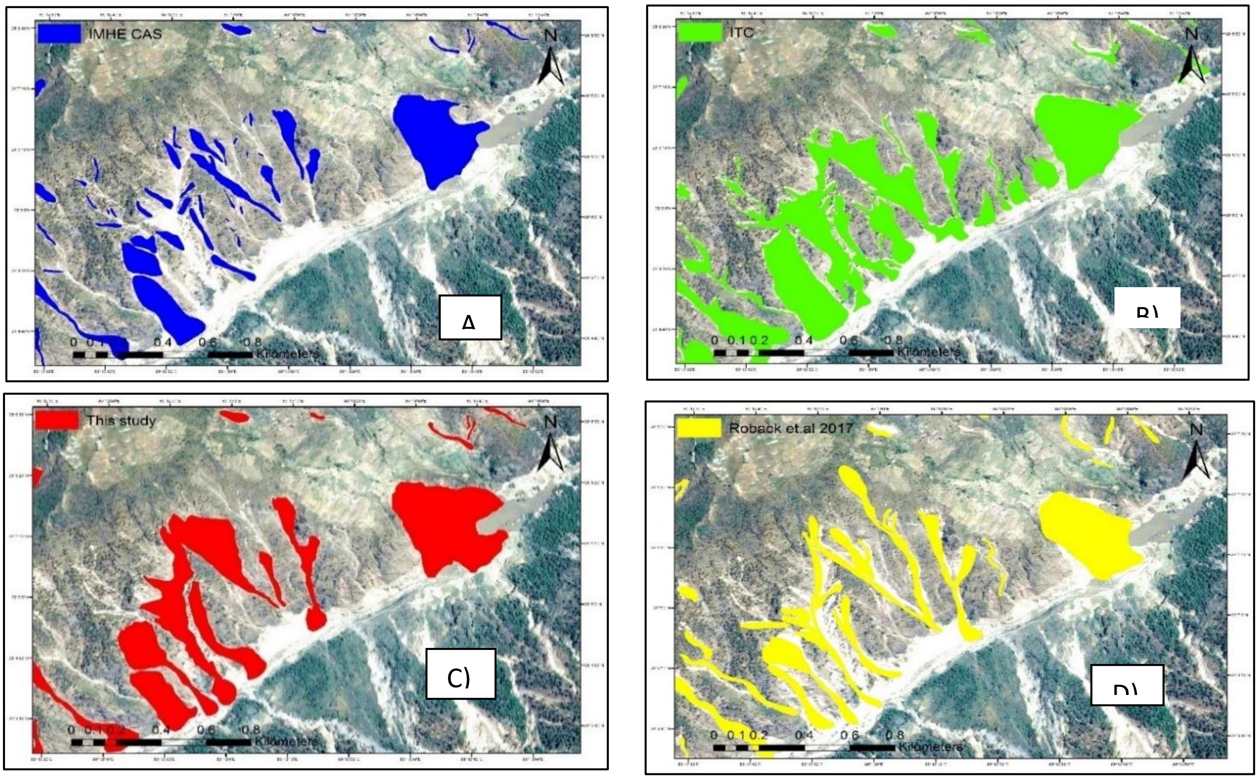


Figure 5.4 Effect of amalgamation for the same area mapped by four different people, in the area near the Trisuli river.A) IMHE CAS B) ITC C) This study D) Roback et.al 2017

5.3. Area frequency analysis

5.3.1. Completeness of the landslide inventory maps for commonly mapped area

The probability of occurrence of landslide size can be given by the power law of Equation 5.1.

$p(x) = cX^{-\beta}$ Equation 5.1

where X are observed values, c is a normalization constant and β is the power-law exponent.

Figure 5.5 shows the power law distribution for medium to large landslides and divergence from the power law towards lower frequencies with a rollover point where frequency decreases for smaller landslides. The trend of the Frequency Area Distribution of most landslide inventories diverges from a power-law for small landslides(Malamud et al. 2004a; Stark & Guzzetti 2009; Guzzetti et al. 2002; Van Den Eeckhaut et al. 2007). The point where this divergence begins is defined as the *cut-off* point(Stark & Guzzetti 2009). For non-cumulative probability density distributions of landslide areas, the peak point of the probability distribution curve after which the probability value begins to decrease for smaller landslides following a positive power-law decay is referred as the *rollover* (Van Den Eeckhaut et al. 2007). However, in some studies, such as Parker (2013), the trend of frequency-area distribution which diverges from a power law for small landslides is referred to as the rollover point. According to Van Den Eeckhaut et al. (2007), In a power law distribution, the slope of the distribution is defined with a power law exponent. The part that is represented by large events is referred to as the power law tail as shown in Figure 5.5 (with a scaling parameter, β). Malamud et al. (2004) investigated four well-documented landslide events and concluded that rollover is a real phenomenon for landslide-event inventories which depends upon the bias and undersampling of the smaller landslides. They modelled the frequency-area distribution for these four inventories and established theoretical curves to estimate the total landslide area triggered by an earthquake or rainfall event

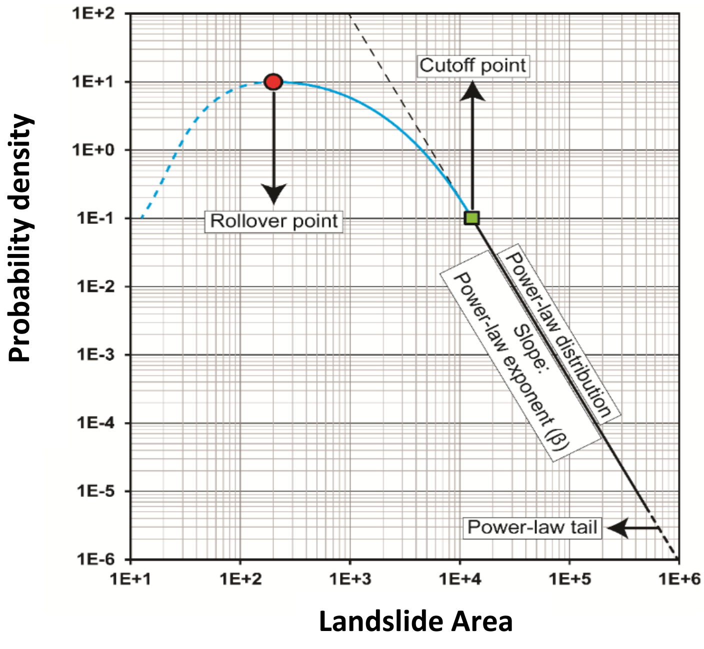


Figure 5.5: Typical frequency-area distribution of landslides (Van Den Eeckhaut et al. 2007; Stark & Guzzetti 2009)

Further distributions have been used to fit the frequency-area distribution of landslides. The double Pareto model describes the majority of the data well, Guthrie & Evans (2004) indicate that the same model is less good at the tails of the distribution. Another method was proposed by Malamud et al. (2004b) who showed that the entire FAD of landslides could be explained by a three-parameter inverse-gamma distribution (Equation 5. 2). This approach also described a way to estimate the landslide event magnitude (mLS), mLS is the indication of the size of the landslide triggering event, regarding the number and size of landslides, it gives the indication of the severity of the event in terms of landslide occurrence in a particular area for an event.

$$p(A_L;\rho,a,s) = \frac{1}{a\Gamma(\rho)}\left[\frac{a}{A_L-s}\right]^{\rho+1} exp\left[-\frac{a}{A_L-s}\right] \qquad \text{(Equation 5.2)}$$

where ρ is the parameter primarily controlling power-law decay for medium and large values, $\Gamma(\rho)$ is the gamma function of ρ, A_L is landslide area, a is the location of rollover point, s is the exponential decay for small landslide areas, and $-(\rho+1)$ is the power-law exponent Malamud et al. (2004b) provided best fit for power law exponent and gives $-(\rho+1)$ =2.4.

Table 5.4 shows that the power law exponent of three analysed inventory ranges from 1.27 to 1.37 which is lower than 'the given power law function exponent of 2.4 provided by (Malamud et al. 2004a). It is the result of using smaller dataset for analysis, as Malamud et al. (2004b) used three large landslide inventories from around the world.

Table 5.4 Comparison of the frequency statistics of landslide area(Malamud et al. 2004b)

	N_{LT}	Power law Exponent	Rollover Point	A_L km²	min A_L m²	max A_L m²
Roback et.al 2017	498	1.3090	85.1369	3.25	35.50	118805.1101
IMHE CAS	338	1.37.93	289.999	4.20	112.22	151708.91
This study	131	1.3299	299.2794	2.94	121.19	341901.49
ITC	197	1.2756	223.2202	5.04	95.49	764038.12

Minimum landslide area mapped ranges from 35.50m² to 121.19m² for the same area. Also, the largest landslide mapped ranges from 118805m² to 764038m². Causes of these difference are discussed in section 5.2.

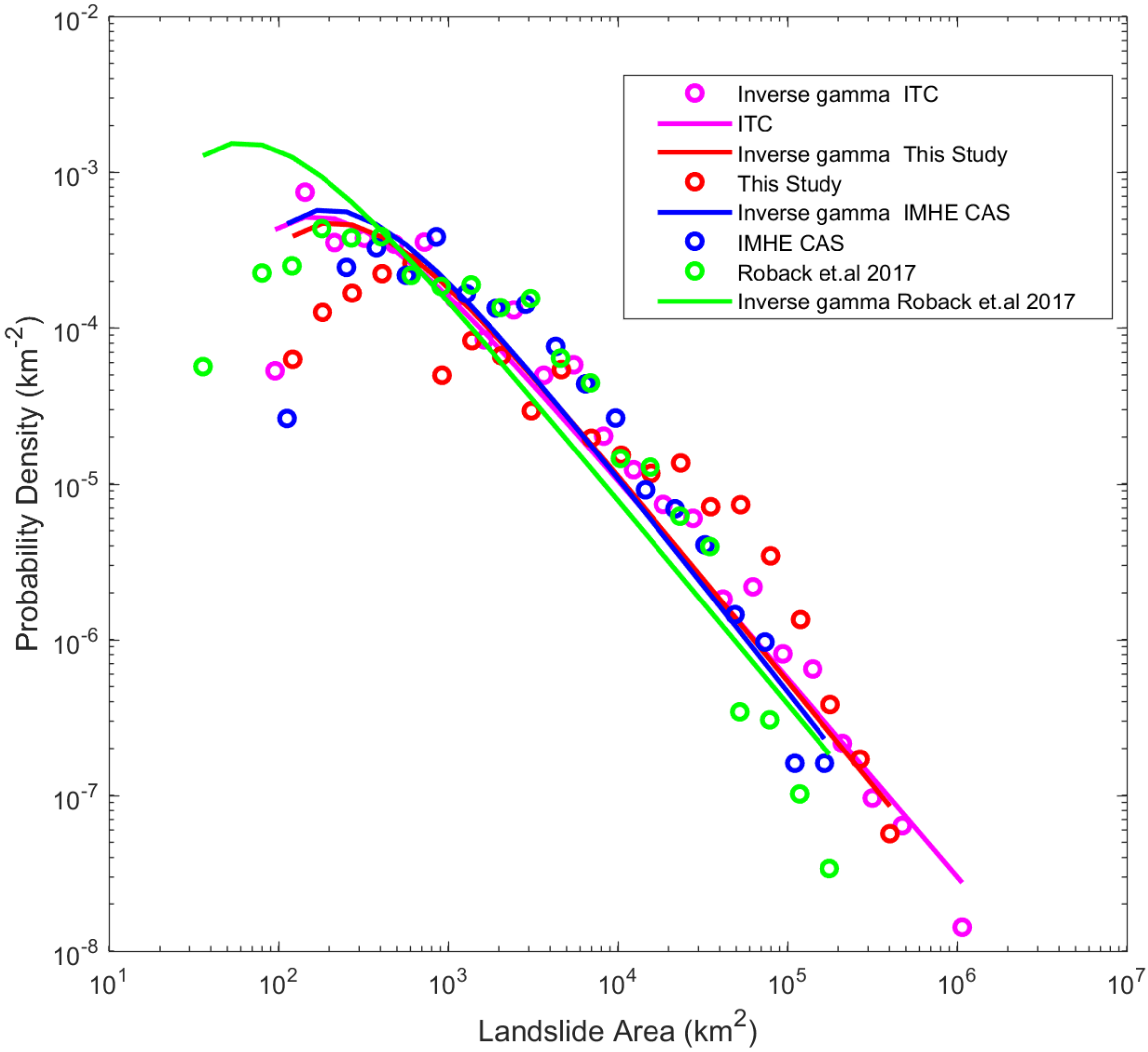


Figure 5.6 Probability density of landslide areas for three different landslide inventories.

There is a zigzag pattern of the plotted landslide probability density to the inverse gamma fit. Differences in the probability distribution and inverse gamma fit can be the result of gaps regarding mapped landslides for given inventories which means that some landslides are missing or not mapped by respective authors due to various reasons discussed in section 5.2. The rollover points for landslides mapped by IMHE CAS and this study are almost similar around 290, but for landslides mapped by ITC, the rollover point is 223 which is nearly 70 points less than other two inventories. For inventory by Roback et al. (2017) rollover point is 85.13 which is small in comparison to other inventories as the distribution of small landslides is well given in inventory. Roback et al. (2017) mapped smaller landslides in detail but for larger and medium size landslides distribution is scattered.

For inventory by ITC, it can be visually interpreted from Figure 5.6 that there is a large gap between rollover point and the smallest mapped landslide in the inventory that is 95.49m². Between the smallest mapped landslide in the inventory and the rollover point, there are many small landslides in the region, but they are not mapped due to earlier discussed the effect of amalgamation, that is smaller landslides as parts of bigger landslides polygons.

5.3.2. Landslide magnitude scale

In the section, an attempt is made to define the landslide event magnitude for four different inventories for cropped region in the study area which was given by Malamud et al. (2004b). As earlier discussed in section 5.3 landslide inventory used for analysis are not complete, and there is the difference in the quality of the inventories. To find the number of landslides with triggering events Malamud et al. (2004b) gave frequency density for incomplete landslide inventories as $f = \frac{\delta N_L}{\delta A_L}$, as the function of A_L.

$f(A_L) = \frac{\delta N_L}{\delta A_L} = N_{LT} p(A_L)$ Equation 5.3

$mLS = log N_{LT}$ Equation 5.4

$mLS = log A_{LT} + 2.51$ Equation 5.5

In these equations N_{LT} refers to total number of landslides in an inventory and A_{LT} refers to total area covered by landslide in km² in inventory.

Table 5.4 showing Landslide-event magnitude mLS obtained using Equation 5.4 (1), Landslide-event magnitude mLS obtained using Equation 5.5 (2)

	N_{LT}	Rollover Point	mLS (1)	mLS (2)
Roback et.al 2017	498	85.1369	2.69	3.02
IMHE CAS	338	289.999	2.52	2.98
This study	131	299.2794	2.11	3.14
ITC	197	223.2202	2.29	3.21

Landslide event magnitude illustrated as mLS= 1,2,3,4,5,6,7,8 in Figure 5.6 are fitted based on frequency area distribution theoretical curves proposed by(Malamud et al. 2004b).Curves given in Figure5.6 for $mLS = 1$ (N_{LT}=10) to $mLS = 8$ ($N_{LT} = 10^8$). Frequency densities of the four inventories for the common area from Roback et.al 2017, IMHE CAS, ITC and this study are shown in Figure 5.6.

From the figure, it can be interpreted that landslide event magnitude mLS (2) provided by Malamud et al. (2004b) corelate with the statistical results obtained from Equation 5.5. But mLS (1) do not corelate with the results of plotting Frequency density values with theoretical lines. It gives the result that landslide area plays an important role for assigning landslide event magnitude than total number of landsldies in an inventory. Landslide event magnitude gives the severity of event for substantially incomplete landslide inventories hence makes it essential parameter for comparison of landslide inventories.

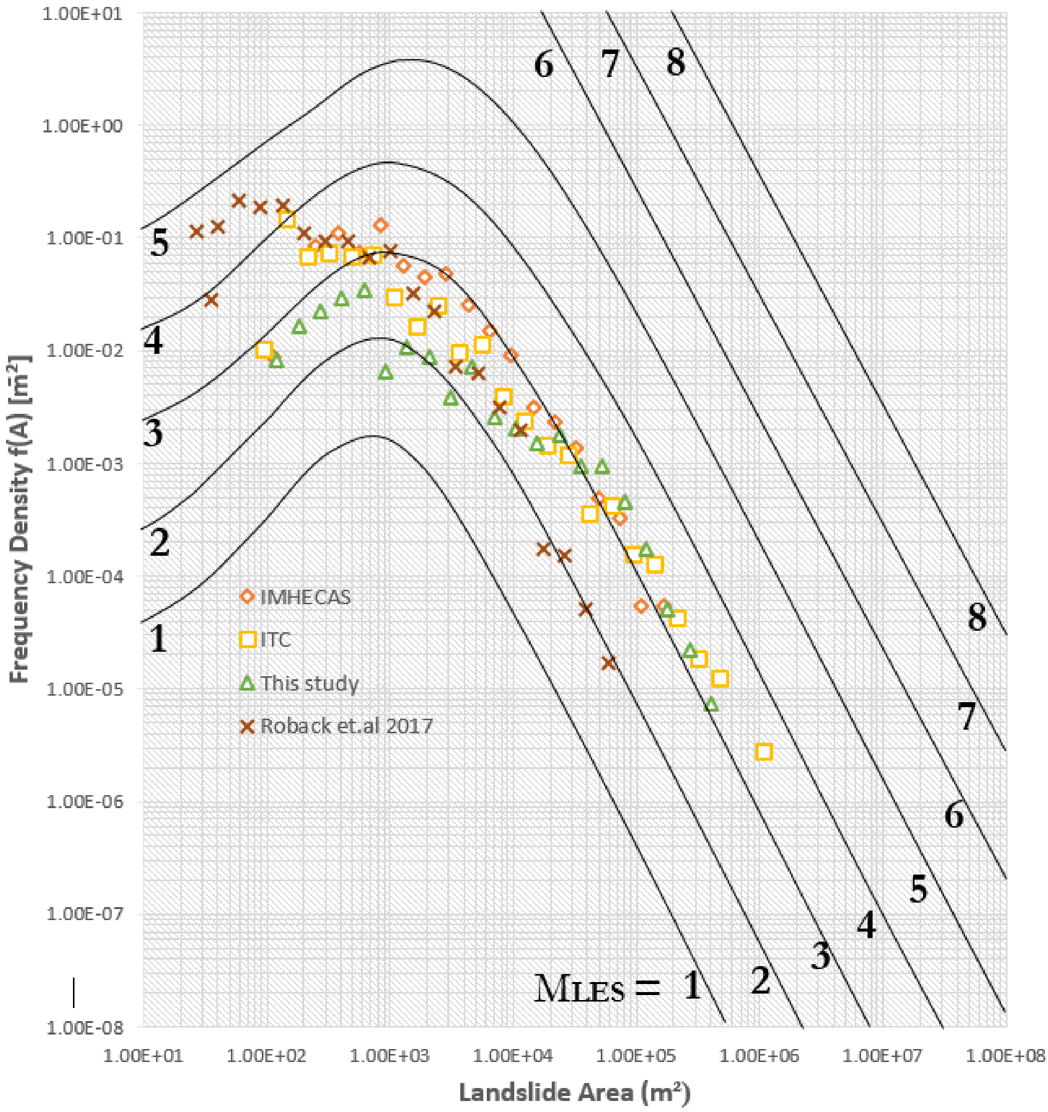


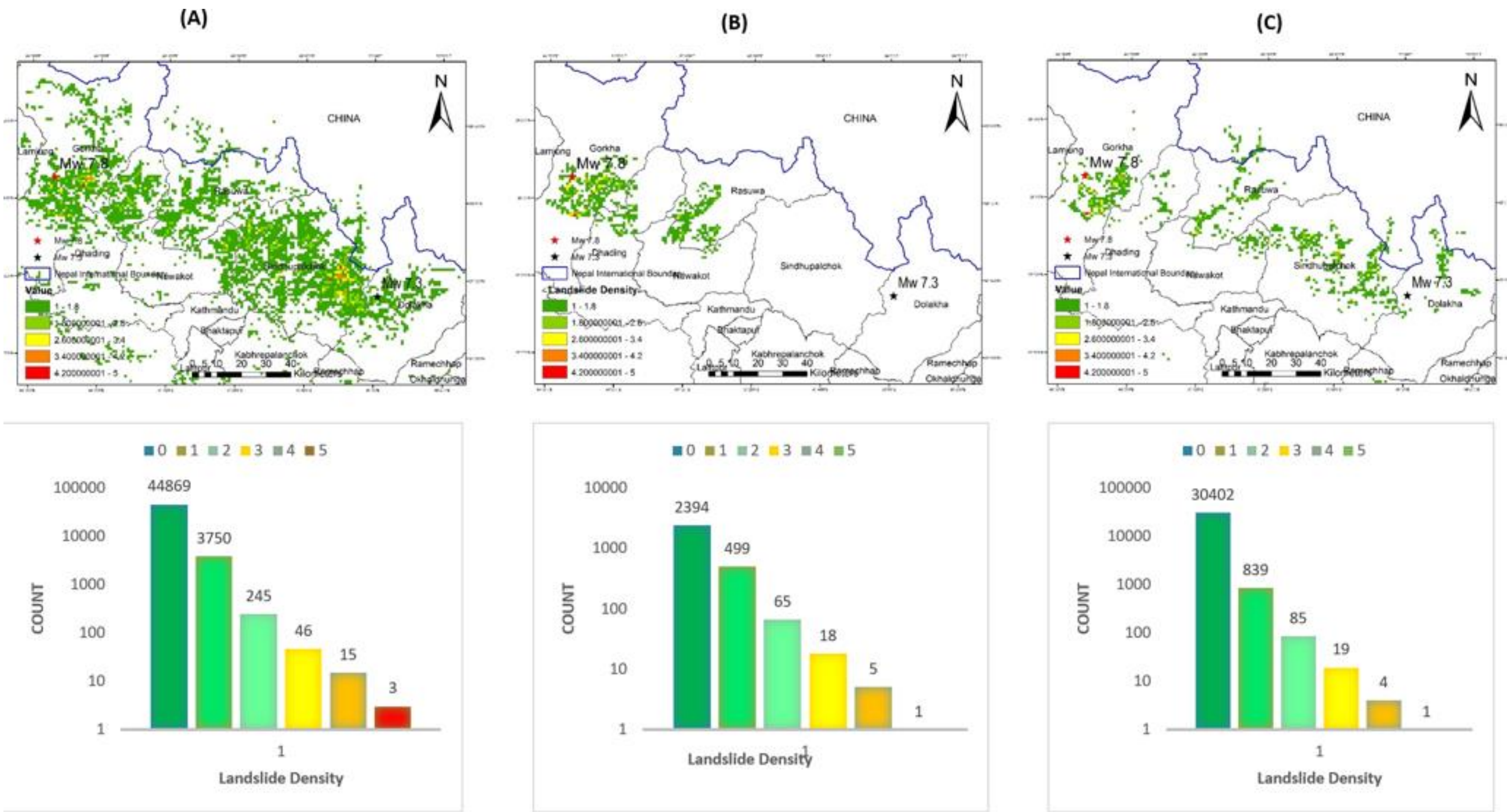
Figure 5.7 relation of Landslide event magnitude and frewuency area distribution for four landslide inventories.

5.4. Comparison of landslide density per square kilometre for six different inventories for Gorkha event

Six landslide inventories for the Gorkha event were collected. A detailed description of inventories used is given in Table 5.1. For analysing landslide density per square kilometre point based inventories were used. Table 5.1 shows collected inventories, three polygons based, two points based and one polyline based inventories. Feature to point tool is used in ArcGIS, then the Spatial Analyst tool for point density was used to show landslide density per square kilometre for the selected inventories. Figure 5.8 shows landslide density distribution of selected inventories for the Gorkha event, all the inventories are coseismic and prepared using post-earthquake satellite imageries.

A detailed explanation of data used to prepare the inventories is given in Table 5.1. There is a significant variation in the number of landslides mapped for the Gorkha event; it ranges from $N_{LT} = 2117\ to\ N_{LT} = 24915$. None of these inventories classified the types of landslides as proposed by Cruden, and Varnes, (1996). Sources of mapping used varies from high resolution imageries of about 20 cm resolution to Google Earth images having resolution of about 2 meter. Out of six inventories only four inventories have defined the domain of the study area. Landslide density analysis results illustrated in figure 5.8 shows that most of the landslides were concentrated in Gorkha and sindhupalchock districts in all most all the inventories, the southern part of Rasuwa district is also severely hit and can be interpreted from the figure. Differences in the density of landslides at a particular area depend on the factors discussed in section 5.2. Areas near dholaka and Sindhupalchok districts show high landslide density; it was the result of the aftershock of 12 may 2015 in Dholaka district.

The Higher density of landslides in Figure 5.8 (a),(c),(f) is the result of mapping total number of landslides mapped for the particular event, these inventories have been done after the aftershock of 12 may 2015. Another factor that affects the density of landslides is the coverage of mapping area.


(A)
(B)
(C)
CHINA
N
Mw 7.8
Mw 7.3
Gorkha
Lamjung
Rasuwa
Nuwakot
Dhading
Sindhupalchok
Dolakha
Kathmandu
Bhaktapur
Kabhrepalanchok
Ramechhap
Okhaldhunga
Nepal International Boundary
Value
Landslide Density
1 - 1.8
1.800000001 - 2.6
2.600000001 - 3.4
3.400000001 - 4.2
4.200000001 - 5
0 5 10 20 30 40 Kilometers
0 1 2 3 4 5
COUNT
Landslide Density
1
44869
3750
245
46
15
3
2394
499
65
18
5
1
30402
839
85
19
4
1
100000
10000
1000
100
10
1

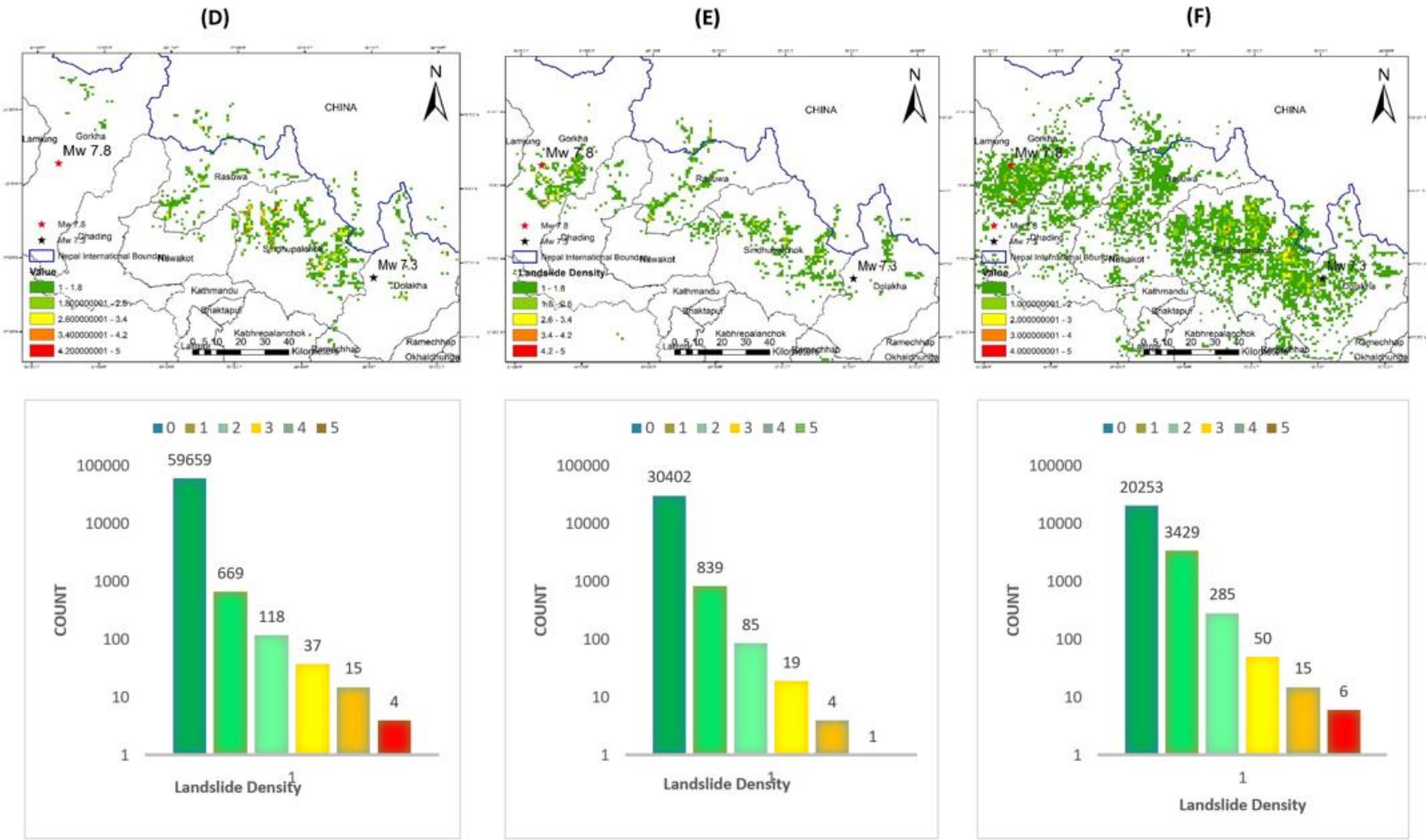


Figure 5.8 Landslide density per kilometre square analysed for 16 landslide affected districts in Nepal for six different inventories A) Roback et.al 2017 B)ITC, C) IMHE CAS D)Durham-BGS, E) Kargel et.al 2016, F) Gynayawali et.al 2016.

6. DESIGN OF THE NATIONAL LANDSLIDE INFORMATION SYSTEM

6.1. Current situation of landslide management in Nepal

In this section put emphasis on the current availability of landslide inventories in Nepal. After the Gorkha earthquake several attempts have been made to carry out landslide inventory mapping of the affected area which covers approximate area about 10000 km² located in Nepal and China (Goda et al. 2015; Shrestha et al. 2015; Valagussa et al. 2016; Chigira 2015; Kargel et al. 2016; Dahal 2015; Gnyawali & Adhikari 2016; Robinson et al. 2017; Roback et al. 2017; Martha et al. 2017).

Table 6.5 *Landslide inventories related to the pre-earthquake situation (Yellow) and post Gorkha earthquake (Blue) in Nepal, Field Based Inventories (Pink).*

Landslide inventory	Number of landslides	Point/ Polygon/ polyline	Classification of type of landslides Yes/No	Area covered	References
C.D.E.S. T.U. Nepal	5003	Polygon	Yes	Nepal	(Pokharel & Bhuju 2015)
ICIMOD Koshi River Basin 1992	3559	Polygon	No	Koshi River Basin	(Zhang et al. 2016)
ICIMOD Koshi River Basin 2010	3398	Polygon	No	Koshi River Basin	(Zhang et al. 2016)
Valagussa et al. 2016	4300	Polygon	No	Gorkha earthquake 2015	(Valagussa et al. 2016)
ICIMOD	5159	Polygon	No	Gorkha earthquake 2015	(Gurung & Maharjan 2015)
BGS and Durham University	533	Point	Yes	Initial earthquake of Mw7.8	(Jordan et al. 2015)
USGS	24915	Polygon	Yes	Gorkha event covering both after shocks	(Roback et al. 2017)
Martha et al. 2016	15551	Polygon	Yes	Gorkha earthquake 2015	(Tapas R. Martha et al. 2016)
IMHE CAS	2645	Polygon	No	Gorkha earthquake 2015	(Zhang et al. 2016)
ITC	2513	Polygon	No	Gorkha earthquake 2015	Tanyas (unpublished data)

Durham University	2117	Polyline	No	Gorkha earthquake 2015	(Colm Jordan 2015)
MacDonald, Dettwiler and Associate (MDA)	333	Polygon	No	Initial earthquake of Mw7.8	(HDX 2015)
British Geological Survey	182	Polygon	Yes	Initial earthquake of Mw7.8	(Jordan et al. 2015)
Kargel et al. 2016	4312	Polygon	No	Gorkha earthquake 2015	(Kargel et al. 2016)
Gnyawali and Adhikari 2016	19332	Polygon	No	Gorkha earthquake 2015	(Gnyawali & Adhikari 2016)
DSCWM field based Inventory for Rasuwa District	37	Detailed landslide mapping sheet	Yes	Lower Phalakhu Khola sub-watershed	
DMG field based inventory		Detailed landslide mapping along with geological assessment	Yes	Rasuwa	
Mountain Risk Engineering Unit, Tribhuvan university		Polygon and detailed landslide	Yes	Rasuwa, Dhading, Gorkha	
Feed Pvt. Ltd. Field based inventory for Mailung Khola Power plant		Polygon	Yes	Along Trishuli River, Rasuwa	
Professor Dhital report on Mailung Khola Hydropower Project	7	Polygon and detailed geological assessment	Yes	Mailung Khola, Rasuwa	

In (Table 6.1) there are 12 landslide inventories related to the Gorkha earthquake, and there is a variation in a number of landslides for the same event. Most of the inventories that were collected are related to co-seismic and post Gorkha event landslides. Some of the inventories were accessed through the online portal of earthquake response (HDX 2015), but for the pre-earthquake inventories, authors were contacted to get their personal databases. Most inventories are polygon based hence enable statistical analysis of area distribution (Malamud et al. 2004a). There are some point based inventories just after the main event carried out for ICIMOD by Gurung and Maharjan (2015) and BGS (Jordan, 2015). There is also one inventory based on polylines by Jordan et al. (2015) from Durham University. Out of 15 inventories, only four inventories follow a categorisation based on the type of landslides. Other inventories just give the landslide polygon, and there are no other attributes added for each landslide except landslide area covered by a landslide.

Just after the main event of Gorkha earthquake several attempts were made to map landslides in the probably affected areas by teams from ICIMOD Gurung & Maharjan (2015), Kargel et al. (2016), NASA-USGS earthquake response team Briggs et al. (2015), Durham University and BGS Jordan, (2015), Chinese Academy of sciences

Zhang et al. (2016) and many more. In the study by Kargel et al. (2016) they were able to map 4312 co-seismic and post -earthquake landslides in six areas of interest that include Manaslu, Langtang, Cho oyu, Anapurna, Ganesh Himal and Everest. In the study, they also surveyed 491 glacier lakes for damage caused by the earthquake. A total of 19332 landslides were mapped by Gnyawali & Adhikari (2016) covering an area of about 61.5 km² using Google Earth imagery. Researchers from ISRO in India like Martha et al. (2017) mapped a total of 15551 number of landslides using object-oriented image classification, for the Gorkha earthquake covering an area of 90.2 km². It included the landslides from the Mw 7.8 Gorkha main shock from 25 April 2015 and the Mw 7.3 Dolakha aftershock on 12 May 2015. The time period used in Martha et al. (2017) study ranges between 27 April 2015 to 19 May 2015. In the collected dataset variation in large number of landslides was the result of delineation of landslides using high-resolution satellite imageries with spatial resolution ranging from 31 cm Worldview-3 to 5 meter Resourcesat-2 Imageries. Another recent attempt to map landslides for the Gorkha earthquake by Valagussa et al. (2016) and a total of 4300 co-seismic landslides were mapped using Google Earth satellite images from 2 may 2015 to 6 June 2015. Recently landslide inventory related to Gorkha earthquake was given by Roback et al. (2017) they covered 24915 landslides which covered most of the area affected by the quake. Large quantity of landslides is the result of using the high resolution Worldview/GeoEye Satellite imagery during the mapping. Roback et al. (2017) also differentiated source area and body of the landslides which makes it distinct from other collected inventories in this study.

There are three rainfall induced collected during field work and from various sources (Table 6.1). A total of 3559 landslides were mapped by Zhang et al. (2016) for the period of 1992 for Koshi River basin and 3398 landslides for the period 2010. Landslides were mapped using high resolution satellite imagery and topographic maps. Zhang (2016) analysed three time period landslide for koshi river basin from 1992, 2010 and 2015 Landslides were mapped into two regions the lesser Himalayas and transitional belt, and results shows that southern slopes of the Himalayas have more landslides than the northern side and rainfall induced landslides are small and shallow with elevation less than 1000 meters due to heavy precipitation in southern parts of the country. Another pre earthquake inventory was compiled by Pokharel & Bhuju (2015) from central department of Environmental science, Tribhuvan University by involving 13 graduate students, they mapped 5003 landslides covering . they covered 72 district of Nepal and classified landslides into types which covered slide (2328), flow (899) and complex (844). They have prepared a report on pre earthquake landslide in Nepal and is available from CDES TU. Results shows that Total landslide patches (>1 sq km): 5003; Highest number in Rolpa (258) followed by Bajhang (212), Baitadi (176) and Jumla (175); Lowest in Jhapa, Rautahat and Siraha (8); Landslide area: Highest in Jumla (8,014,039 sq. m); Lowest in Jhapa with (19,175 sq.m) and Aspect effect: South contained highest number per area (43%) of the total landslides Land use and land cover type: Highest number of landslide in shrubland (782) and dense forest (779); Forest and shrub-land was at highest risk (1844 and 1125 landslides).

In Figure 6.1 all landslide inventories that were collected for Nepal are shown. Spatial distribution of landslides for earthquake affected districts after Gorkha earthquake and Rainfall induced landslides from Koshi river basin is shown. At national scale it is very difficult to differentiate the landslide inventories visually from the figure 6.1 but they are a total of 12 inventories for Gorkha event and three inventories for rainfall induced landslides. But figure 6.1 gives general overview of landslides collected during field visit and other sources. Earlier in section 5.4 detailed analysis and distribution of landslide inventories is given for Gorkha event.

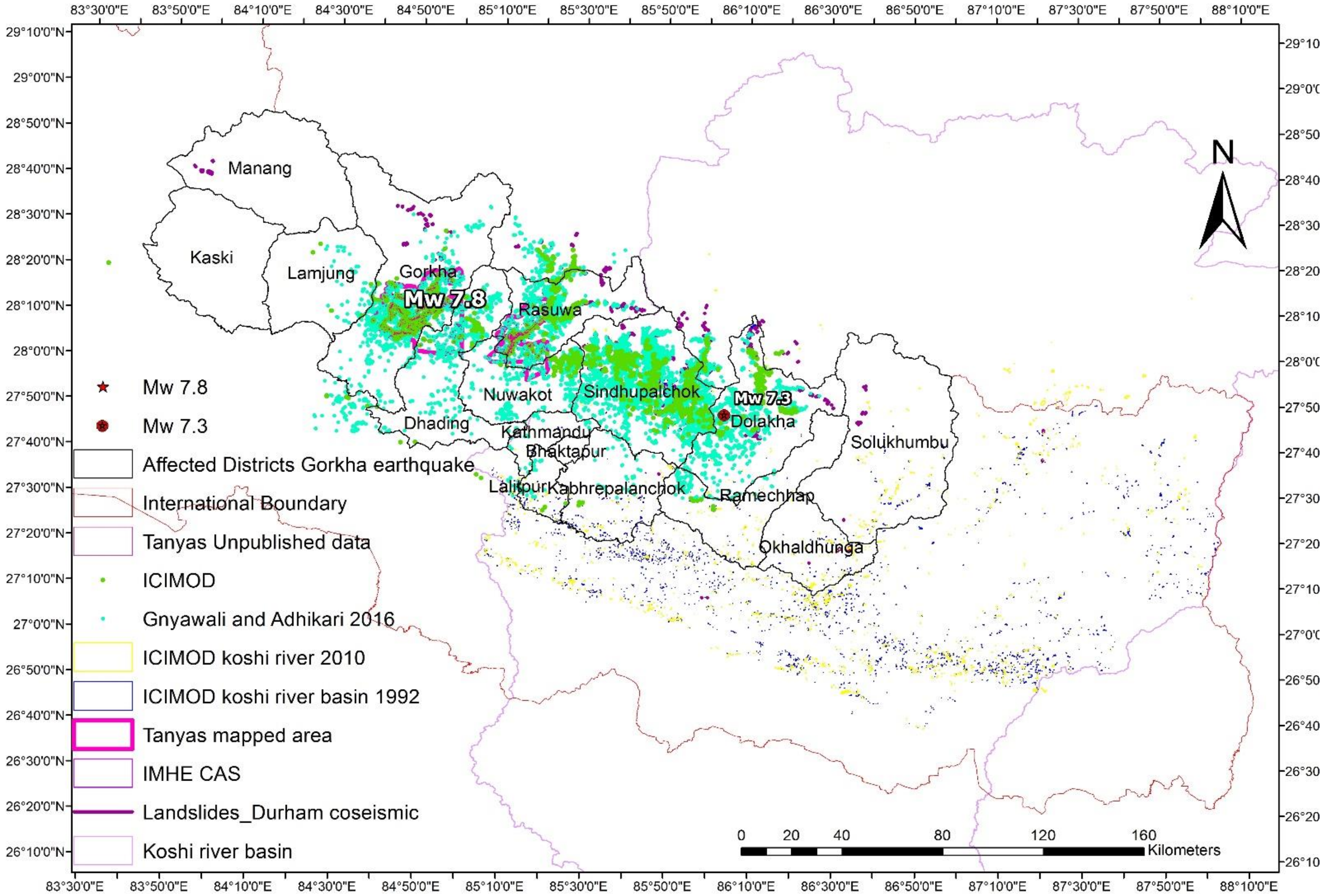


Figure 6.1 Landslide Inventories collected during field visit to Nepal.

An overview of the landslide inventories with the number of landslides is shown in Figure 6.2 A) with differentiation in the type of landslide inventories as points (Red), Polygons (Yellow), Polylines (Purple). There is a considerable variation in a number of mapped landslides in between the inventories because on the mapping methodology adopted for inventorying landslides. Figure 6.2 B) shows Pre earthquake (Blue) and post-landslide (Purple)inventories.

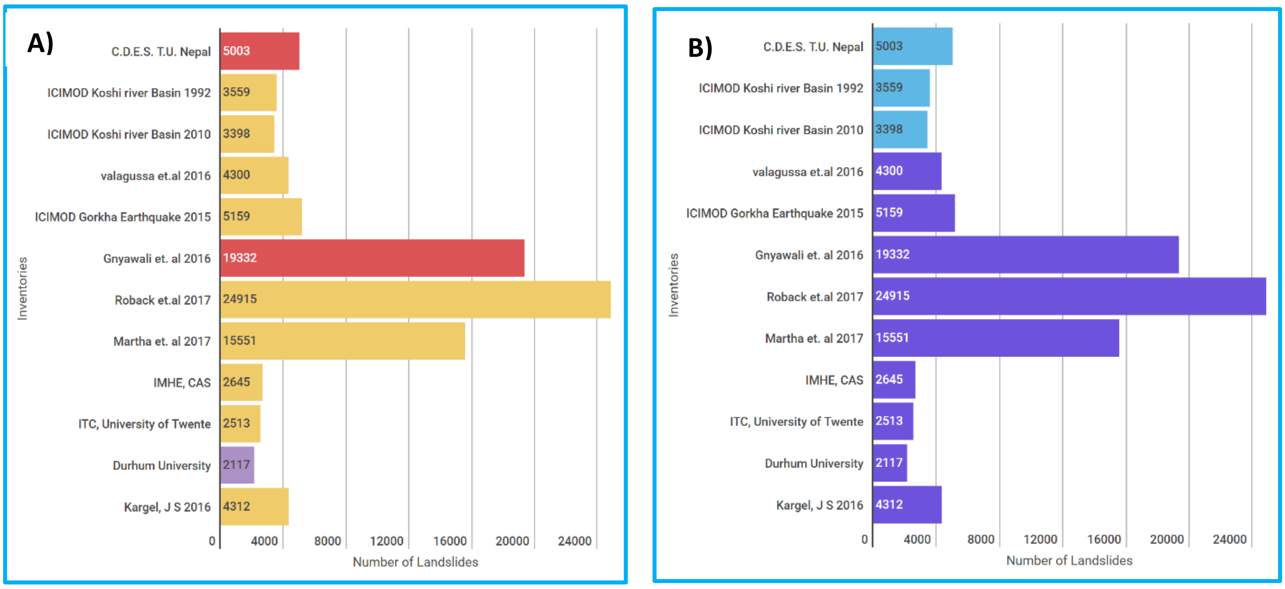


Figure 6.2 A) Shows landslide inventories based on type of mapping (point, polygon, polyline), B) Shows landslide inventories based on triggering factors.

Different landslide inventories have different mapping methodologies and some are in the form of reports like inventory from Pokharel & Bhuju (2015) and other inventories are available as shape files that can be used in a GIS platform. Polygon based inventories illustrated in Figure 6.2 A) have information about area of landslides.

6.1.1. Landslide information management system in Nepal

In Nepal, there is no platform available that has geocoded information about landslides open to the public or to other government agencies. The development of a central landslide information system to report and provide landslide data will facilitate better data sharing among stakeholders and lead to better reconstruction planning and planning of the intervention for the mitigation of the landslide hazard in Nepal. For minimising the impact and consequences of landslides in Nepal, there is a need of incorporating landslide hazard and risk information in the planning process at the regional level (Ghosh et al., 2009).

There are efforts to make landslide databases in Nepal at local levels. In September 2015, a workshop was hosted by ICIMOD under the Koshi Basin programme in collaboration with the department of soil conservation and watershed management (DSCWM) and other expert organisations working on landslides (ICIMOD, 2015a and 2015b). The most significant conclusion of the workshop was the alliance between the different organisations to constitute to a centralised Web-based information system to be hosted by ICIMOD (ICIMOD, 2015b). The system would act as a national landslide inventory. The system will provide harmonised methodology for data selection, storage and reporting of landslides. The Regional Development Initiative (RDI) ensures management of geospatial, multi-thematic and socio-economic data at various levels (ICIMOD, 2013). The regional development initiative was proposed to cover the Hindu Kush Himalayan Region with the objectives of information sharing, maintain data formats and standards and also design and development of information system for this purpose (ICIMOD, 2013). Public access to these databases is restricted, and the information is also not available online. There are also reports available after road blockage maintenance with rural road department offices. The Department of Soil Conservation and Watershed Management (DSCWM) also prepared a landslide inventory but landslide data is compiled into reports, and there is no geocoded information about the landslides.

Several stakeholders are currently involved in landslide related work in Nepal like the Road Department, Land Management Authorities, Forestry Department, Disaster Management Department and the Nepalese Army. These stakeholders have different data requirements. A landslide information system is required that can incorporate information about different landslide characteristics and types. Availability and extraction of landslide data from the system are the important aspects. Reporting of landslides directly in the system, for this, a web portal is needed that is connected to the internet and the central database with Google Earth, Open street maps or other relevant viewer on it. However, it is a very challenging task to identify who can report the landslides in the system and whether they have the ability to do so. To determine the potential users and their needs as well as the potential providers of landslide information, interviews and questionnaires were used during the field work. The objective was to identify a realistic structure of a database, either for users or information providers that could serve in Nepal. As for example, it was locally investigated whether simple users like school teachers can report a landslide event by pointing it out in the reporting system. In that case, the feasibility of schools organising a monthly meeting with the students regarding collecting information of any landslide event occurred in nearby areas and registering it to the system was checked. The first step for setting up this structure was investigating the administrative, organisational set-up in Nepal, across which the information could be collected and disseminated, which can be seen in Figure 6.3. In Nepal smallest administrative unit is the Village Development Committee (VDC) which is headed by VDC head, and at the district level, there is a District Headquarter which manages the different departments. The structure of the administrative organisations will lead to better understanding of the landslide hazard in Nepal.

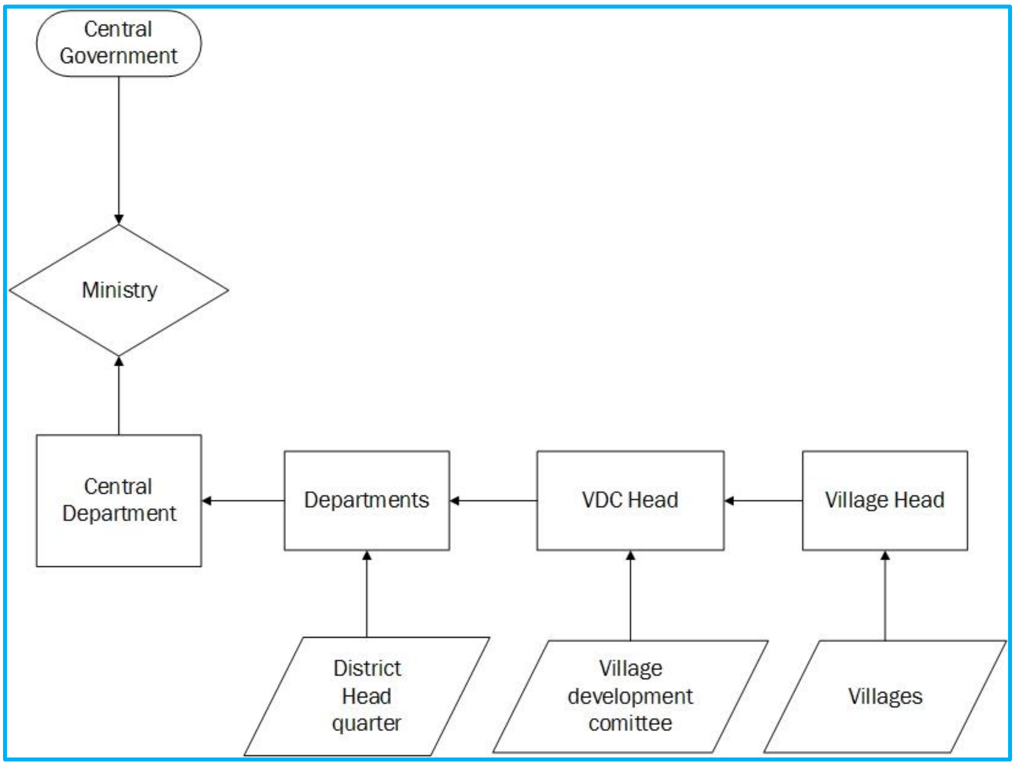
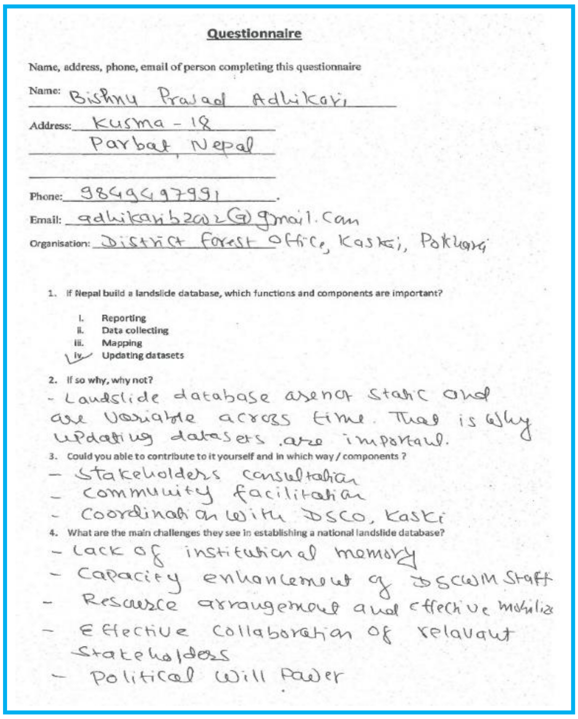


Figure 6.3 Administrative, organisational setup in Nepal.

6.2. Questionnaire for landslide information system

For the identification of stakeholders for the landslide information system, a questionnaire survey was carried out, and organisations are dealing with landslide management were visited. The questionnaire is shown in Figure 6.4 which was conducted for 40 officers from different organisations. Information related to their position in the organisation and how they could contribute to the national landslide information system. Questionnaire survey included information about important aspects of landslides that should be prioritised in the national landslide information system.



Questionnaire

Name, address, phone, email of person completing this questionnaire

Name: Bishnu Prasad Adhikari

Address: Kusma - 18
Parbat, Nepal

Phone: 9849497991

Email: adhikarib2002@gmail.com

Organisation: District Forest Office, Kaski, Pokhara

1. If Nepal build a landslide database, which functions and components are important?
   - i. Reporting
   - ii. Data collecting
   - iii. Mapping
   - iv. Updating datasets ✓
2. If so why, why not?
   - Landslide database aren't static and are variable across time. That is why updating datasets are important.
3. Could you able to contribute to it yourself and in which way / components ?
   - Stakeholders consultation
   - community facilitation
   - Coordination with DSCO, Kaski
4. What are the main challenges they see in establishing a national landslide database?
   - Lack of institutional memory
   - Capacity enhancement of DSCWM Staff
   - Resource arrangement and effective mobiliz
   - Effective collaboration of relavant Stakeholders
   - Political Will Power

Figure 6.4 Sample of questionnaire used during fieldwork to collect information

Potential nodal agencies that could organise and maintain landslide information are the Department of Soil and Watershed management (DSCWM)they look at land degradation, soil erosion, shallow landslides and its relation with vegetation, the Department of Mines and Geology (DMG) looks at rock-related landslides and rockfall and the Department of Water-Induced Disasters (DWID) deals with large scale landslides, and things related to hydro-power, and floods. DSCWM as a central node can guide the growth, development, and oversight of the national landslide information system. Other organisations like Department of Mines and Geology, and ICIMOD, can also provide the technical expertise and workforce. Organisations like DSCWM and DMG already have landslide inventory and socio-economic data for selected districts, but the information is in the form of reports. Hence, there is a need for collaboration between different organisations to set up sustainable landslide information system that has geocoded landslide information at national scale. Several suggestions and requirements of the various stakeholders identified, and organisations that are working in landslide research and mitigation works. Results shown below are concluded from questionnaire survey (Figure 6.4) conducted during the field visit. In questionnaire survey, we asked experts to fill the questionnaire, there were experts from various organisations present at the international conference on "Scientific learning exchange on landslide management and bio-engineering in Nepal: from data to landslide mitigation - new venues for collaboration"(DSCWM 2016).

6.3. Landslide data providers

Landslide data providers are identified during the field after questionnaire survey at various organisational levels in Nepal. Governmental organisations, as well as NGOs and INGO's, were visited and interviewed about what are their roles and how they can contribute to the landslide information in the country and which aspects are most important for National Landslide information system for Nepal. Based on questionnaire survey and interviews Table 6.2 shows the contribution of data providers in landslide information system in Nepal.

Table 6.2 Contribution of data providers towards NELIS.

No.	Organizations	Contribution	
1.	Academic and research institutes.	• They can provide landslide inventory data prepared by them.	• Analogue format reports and also digital landslide inventories prepared for research purposes(Gnyawali & Adhikari 2016).
2.	News and Media	• Geocoded location of the event can be provided by the news and media agencies to the system	• Getting information of landslides for National Landslide Database by searching newspaper archives(Taylor et al. 2015).
3.	Department of Soil Conservation and Water Shed Management.	• DSCWM have landslide information at regional and local level. • They maintain landslide database in their department.	• DSCWM have prepared guidelines to map landslides given by(Pradhan 2016).
4.	Department of Mines and Geology.	• Works for the development of landslide inventory at various levels.	• Can provide regional landslide inventories.
5.	Rural Roads and construction Authority.	• Do not maintain database but have knowledge of landslides in the countryside of getting information from local people through applications for road clearance • Maintenance reports after a landslide blocked the roads.	• They can provide road clearance reports that will help to identify the past landslides.
6.	Department of water induced disaster management.	• Mitigation works for landslide hazard prevention.	• Landslide prevention by constructing Gabion walls and similar preventive measures.

6.3.1. Information available related to NELIS to the Providers:

Based on interviews and surveys functions and requirements of stakeholders working on landslide management are identified and what type of landslide information already available to them and in what format. A detailed description of roles of the organisations in their respective fields is determined and shown in Table 6..3. Also, the information that is available to them that support development of NELIS.

Compare with landslide data from different providers, for example, the landslide data from Academic institutes, are generally based on remote sensing image. The landslide data are used to do the susceptibility, hazard and risk assessment, and include all scales of landslides. For the news and media, generally for large size landslide event

which causes huge casualty or huge damage. For the governmental department, they can supply different kinds of landslide dataset base on their work. DSCWM: Department of soil conservation and watershed management have field based and digital landslide inventories for small water sheds in Nepal, they could transfer there data to digital format as in DSCWM they use GIS platform to map landslides.
DMG: Department of mines and geology have several geological hazard assessment reports after the earthquake based on the field investigations. Data from DMG will enhance the geological hazard data to the NELIS.

Table 6.3 Information available to the Providers regarding landslide data.

No.	Organizations	Available information
1.	United Nations Environmental Programme.	• Location of potential landslides • Eco DRR locations
2.	United Nations Development Programme.	• Relocation planning based on landslide information
3.	National Society Earthquake Technology	• School earthquake safety regulations. • Seismic Vulnerability Assessment of Existing Buildings. • Risk mapping and shelter response planning
4.	Academic and research institutes.	• Pre-earthquake landslide inventory by CDES Tribhuvan university
5.	Department of Soil Conservation and Water Shed Management.	• Landslide inventory • Guidelines for mapping landslides for visual image interpretation and also for mapping of landslides using Landsat images. •
6.	Department of Mines and Geology.	• Landslide inventory. • The geological map at the regional level.
7.	National Reconstruction Authority	• Building data • Population data • Agricultural land data • Transport data

8.	Department of local infrastructural development and agricultural roads	• Information on the rural road network. • Clearance records of roads after landslides.
9.	Department of water induced disaster management.	• Landslide data available at watershed level

6.4. Identification of Users

After visiting several organisations during the field visit, a list of stakeholders for the landslide database was compiled, which is listed in Table 6.4. The different organisations can be grouped into four categories which are National organisations, international research groups, Academia, and International organisations. Later in section 6.2.2.1 how and which information users can get from NELIS is discussed.

Table 6.4 Stakeholders working on landslides research in Nepal

No. / Organisations	1.	2.	3.	4.	5.	6.
National Organizations	Department of Water Induced Disaster Management	National Reconstruction Authority, Department of geology	Department of Mines and Geology, y	Department of Forests, Ministry of Physical Infrastructure	Rural Roads and Construction Authority.	Department of local infrastructural development and agricultural roads
International organizations	United Nations Development Programme (UNDP)	United Nations Environmental Programme (UNEP).	United Nations Human Settlement Programme (UN-HABITAT)	The World Wildlife Fund (WWF)	Food and Agricultural Organization (FAO).	
International Research groups	Kyoto University with funding from Japan Science and Technology Agency in collaboration with Hirosaki University, Yamagata University	ITC, the University of Twente, The Netherlands	The University of Lausanne, Institute of Earth Sciences	University of Bonn, Germany;	Institute of Mountain Hazards and Environment, CAS, China	The University of Milano-Bicocca, Department of Earth and Environmental Sciences
National Universities and Research groups	TU Central Department of Environmental Science	Nepal Academy of Science and Technology	President Chure-Tarai- Madhesh Conservative on programme.	The Mountain Institute.	Department of Geography, Tribhuvan University	Institute of Engineering, Pulchowk, Tribhuvan University

6.5. Proposed National Landslide Information System for Nepal

After evaluation of stakeholder's roles and requirements for the National landslide information system, many suggestions are resulting from the questionnaire survey (Figure 6.1) for the development of Nepalese Landslide Information System(NELIS). The results of survey are analyzed and shown in figure 6.5 which shows components of the NELIS that should be prioritized during development. Four components, reporting of landslides (17.58%), Data collection from various sources after an event (23.08%), updating of already existing datasets (32.98%)and mapping landslides using different tools (26.37%). Experts of landslide research in Nepal were interviewed and results shows that in Nepal after the Gorkha event most of mapping or data collection work has been carried out and there is a need to update those datasets. There has been mapping of landslides after the Gorkha event and many international researchers and national organisations were involved. From field visits and collecting data about existing landslide inventories, it can be concluded that landslide inventory data are not available to the public and it is very difficult to get permissions from authors to share the data to external scientific researcher or organisations.

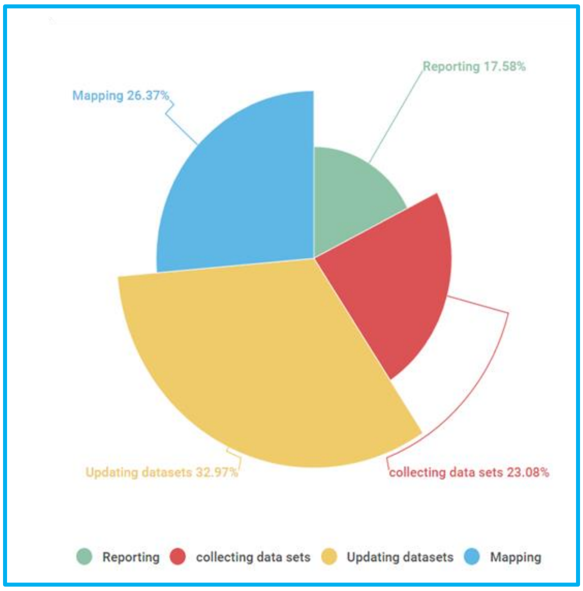


Figure 6.5 Showing results of questionnaire related to which components should be prioritised in development of NELIS.

There are some suggestions and recommendations for the development of the NELIS based on the Questionare survey discussed in section 6.2.

a. Some of the organisations have already done data collection and reporting at large scale, but there is a lack of transferring this knowledge into preparing hazard maps for mitigation works.
b. There is a need for proper guidelines for mapping landslides, already mapping guidelines are prepared by the working group 2 presented during DSCWM (2016) conference in Kathmandu in 2016 but still there is a need to improve it.
c. Landsliding is a dynamic process, so already collected data are not sufficient and requires updating of datasets.
d. Use of remote sensing data is not enough so field verification should be carried out.
e. Universities and academia can contribute to reporting and information sharing of research work in landslide hazards that will help in methodological advancement.

f. There is a need for transparency and exchange of information to mitigate the effects of landslides.
g. Users should be able to switch between different layers such as land use, settlements and could easily get the information as per requirement.
h. Coordination between organisations is necessary to avoid duplicate efforts.

Not all requirements and suggestions can be included in the development of system keeping in mind the technical as well as management limitations at the national level. So, after analysis of user requirements and contribution of landslide data a conceptual structure of the National landslide information system is proposed.

6.6. Proposed structure of the National landslide information system for Nepal

In order to provide a more comprehensive inventory for landslides, the new landslide database management system NELIS (Nepalese Landslide Information System) is proposed. The main tasks of NELIS are to store and register detailed data retrieved by field mapping and to provide a platform for sharing of landslide information. For the acquisition of data on the ground and their compatible move into the database, a customised landslide mapping sheet is proposed modified after Pradhan (2016), which contains essential core attributes and additional information (Van Den Eeckhaut & Hervás 2012; Hervás 2013; Jäger et al. 2014)of landslides. In order to provide a great premise to further inquiries and appraisals, NELIS aims at a comprehensive coverage of all possible landslides in Nepal including old landslides by organising mapping campaigns in areas of special interests. NELIS will be a detailed, spatial database with temporal information, supported by complementary data (Van Den Eeckhaut & Hervás 2012; Hervás 2013; Jäger et al. 2014)from different arrangements of maps produced after regional studies. However, available information will enable different queries and analyses from a region prone to landslides. The design will be preferably based on free Open Source Softwares (PostgreSQL and PostGIS).

6.6.1. Information sources and data collection:

Different sources of information can be used for compiling landslide data.:
The NELIS can be continuously updated and expanded through passive and active means. Passive means like searching for data in the news and social media using keywords, and active means like fieldwork, papers, journals, reports, citizen science. The landslide database can be generated with data sets obtained from multiple sources grouped into categories depending on the type and format of information provided , such as:

1) Historical records such as dissertation, research papers, can provide information on events that occurred in past. Landslide information is only available in analogue format and not consistently recorded. From historical reports information about occurrence of the landslides can be available.
2) Reports for example, Road maintenance reports by rural road department. There are field based technical reports by DSCWM, DMG and Academia. Field based reports gives detailed information about landslides in a particular region for example DMG report on geological hazards in Rasuwa district which was collected during field visit.
3) Existing landslide inventories: There are many existing landslide inventories discussed in section 6.1 that can be used as the input source for the NELIS.
4) News and social media: News and media can be a importnant source of landslide information. In nepal Himalayan times digital archieves contains news about landslides occurrence in the country. They also show landslide events on a digital platform with date and location.
5) Local community involvement: Local communites have best knowledge about their surroundings hence information from local people about landslide occurrence can be very crucial.

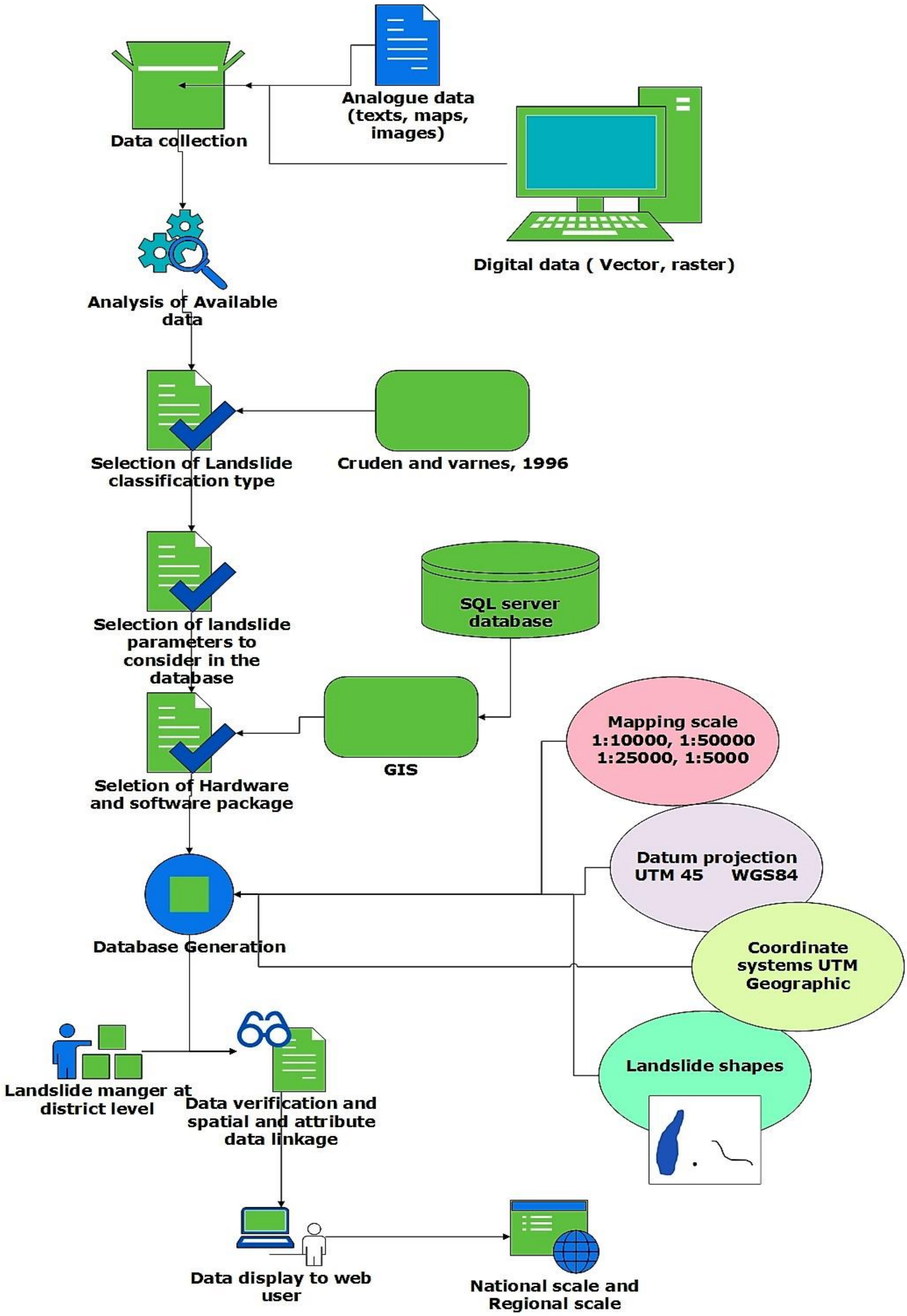


Figure 6.6 Flowchart showing the process proposed to create the NELIS.

6.6.2. Landslide data

The landslide attribute data is represented by topographical and administrative details, date of the event, landslide type, the number of losses and buildings damaged, triggers. To achieve a simple and standardised mapping routine and to ensure homogeneous datasets there should be proper guidelines to map landslides that are simple yet gives atmost information about landslide event. The dataset will be integrated by information on causes and triggers, age and activity of landslides. Altogether, the dataset will provide base data and background for various assessments (modelling, statistical queries, etc.) of slope susceptibilities and landslide hazards (Martha et al. 2016).

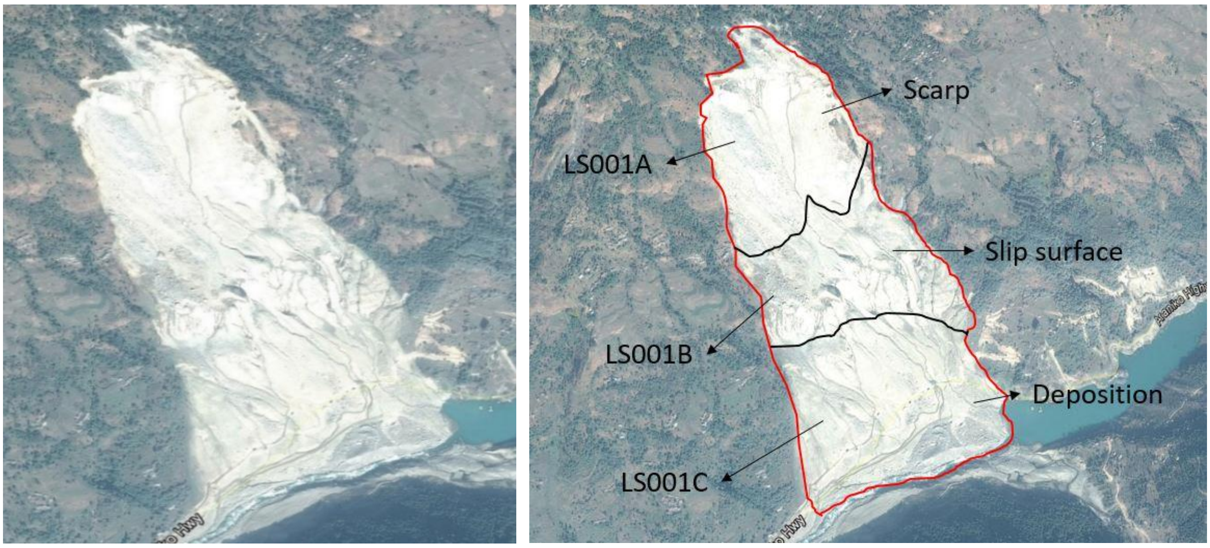
Different providers can have landslide data in various formats like digital data (vector point and polygon data) and analogue data (reports, road maintenance registers) hence make it difficult to integrate them into the system so, to integrate data into the system a landslide manager will check the information provided from different sources and then compare them and integrate the landslide information after verification based on field visit.

For a better exchange between different platforms landslide polygons should be mapped as single polygons using shape files vector format where each landslide should have a unique identifier and should have the following attributes:

a) Type of landslide following the Cruden, D.M., Varnes, D.J. (1996)classification.
b) To differentiate between initiation and accumulation areas of the landslide.
c) The depth of landslide in two classes shallow and deep. Doing this is crucial and may only be adequately done based on field validation. It requires training of the field teams to reduce the subjectivity as much as possible.
d) Volume of landslide (can be calculated in GIS by multiplying depth with area);
e) Indicates if the landslide blocked the drainage, in four classes. Here the temporal information is relevant. When mapping the coseismic landslides, it should be shown if the landslides blocked the river, partially or entirely.
f) Information about the observed damage can only be done for landslides that are validated in the field, but it is an important characteristic that should be used in the risk assessment later.

Table 6.5 Showing attribute table for mapping landslides.

Slide	Part	Type	Subtype	Body	Damage	Blocking river	Remarks	Mapped by	Checked by
LS01	A B C	Slide Slide slide	Rotational rockslide	Scarp Slip surface Deposition	- - -	- - completely	Any relevant remarks	Name of the person who mapped the landslide	Name of the individual who checked the landslide data



Original image *Digitized landslide polygons*

Figure 6.7 The following figure illustrates the guideline to map the landslide.

6.7. Database design and generation

In few data sources, like from ICIMOD (2015), affected area details are already available in digital format. There are two types of landslide inventories available from ICIMOD for the Gorkha event one is point based, and another is polygon based inventory. In the inventory map, the location is represented by point..

An advantage of Nepal Landslide Information System is that it is based on exclusively OpenSource software. The object-relational DBMS will be based on PostgreSQL, with Structured Query Language standards, providing all functions of SQL as a database language for a generation, and manipulation of stored data and data queries. To process and store large volumes of spatial data, PostGIS can be integrated as an extension for PostgreSQL. PostGIS not only improves the storage of GIS information in the Database management system, but also offers spatial operations, spatial functions, spatial data types as well as a spatial indexing enhancement Obe and Hsu (2015) with the objective of a reasonable visualization of data, the database can be related to the open source geographic information system (GIS).

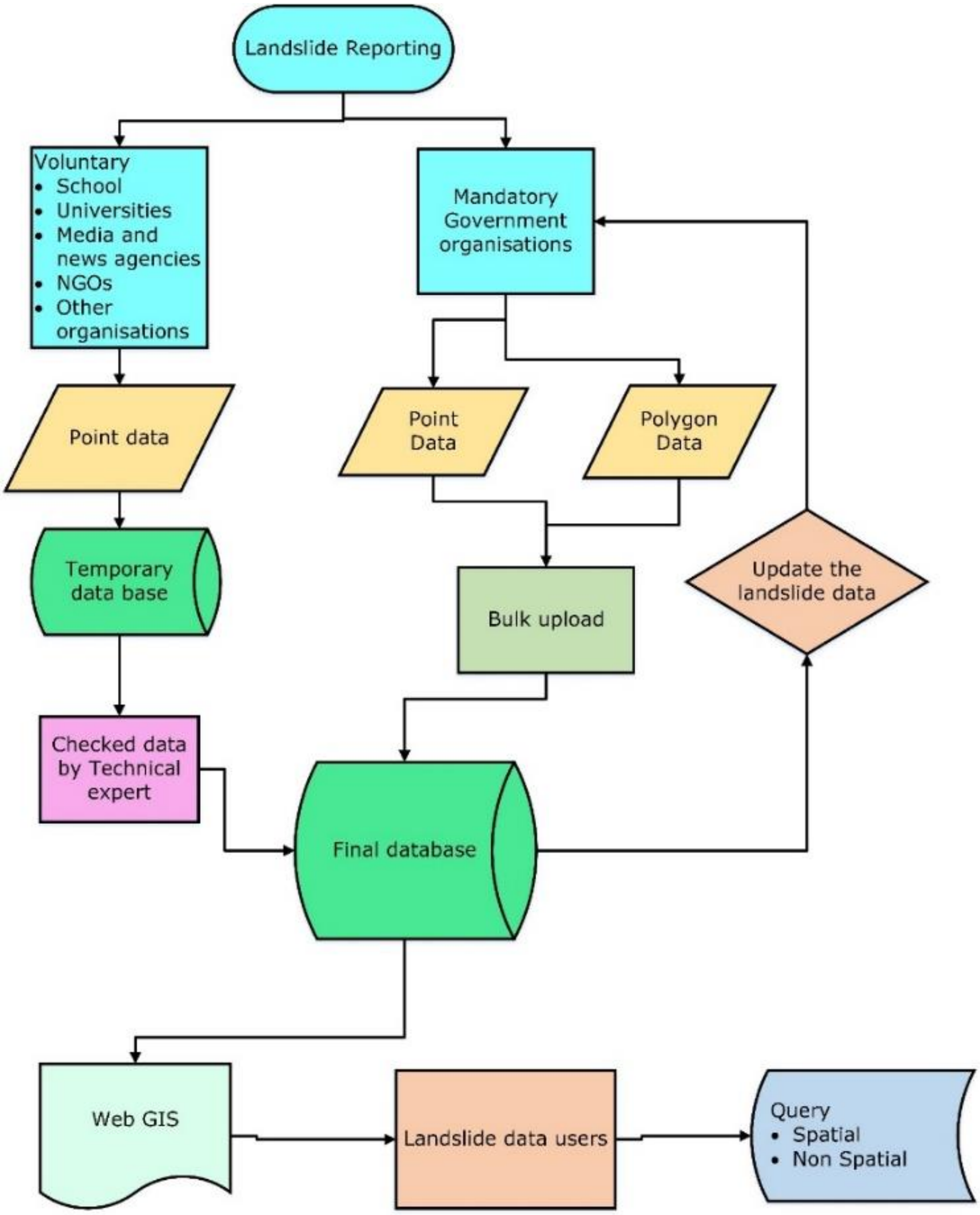


Figure 6.8 Simplified Database structure for NELIS.

6.7.1.1. Landslide reporting

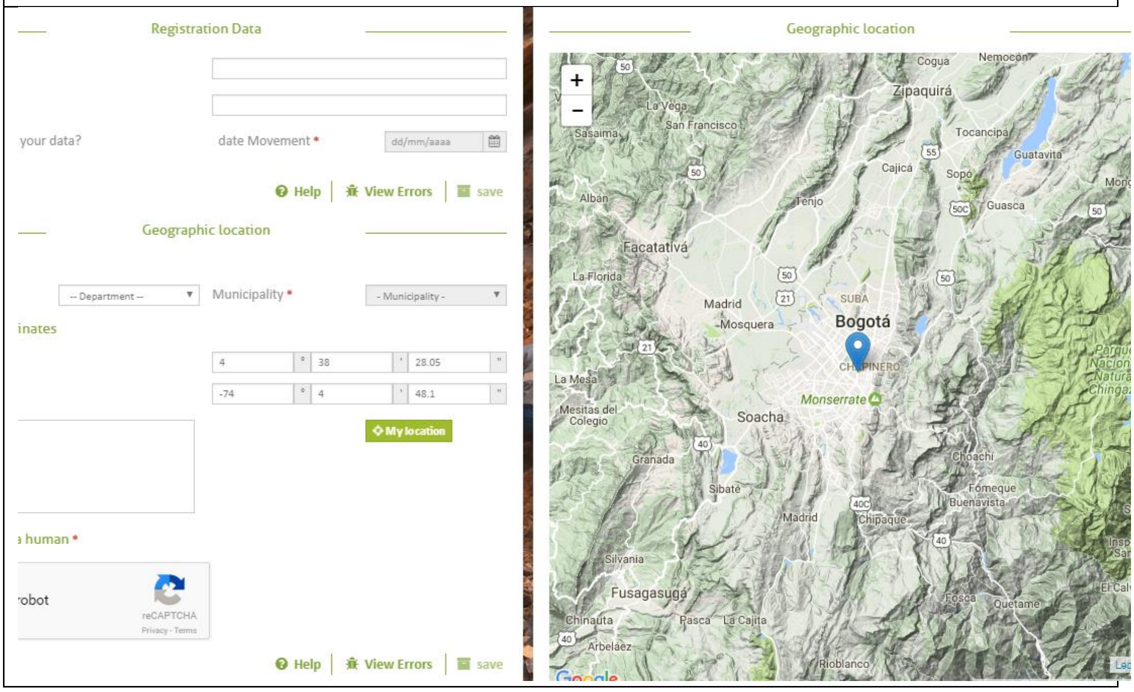
Public reporting

Local public can directly report landslides into the system. The NELIS will provide the users an opportunity to participate in mapping process.

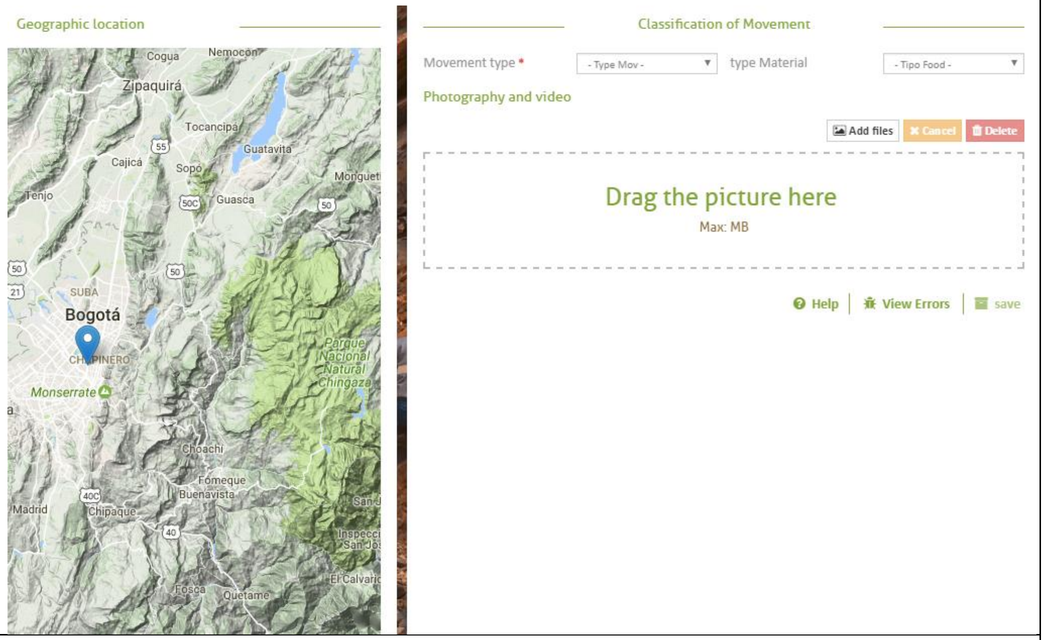
There are steps to report landslide in to the NELIS. Images are taken as an source of explanation taken from (SIMMA 2017).

Table 6.6 Landslide public reporting Steps.

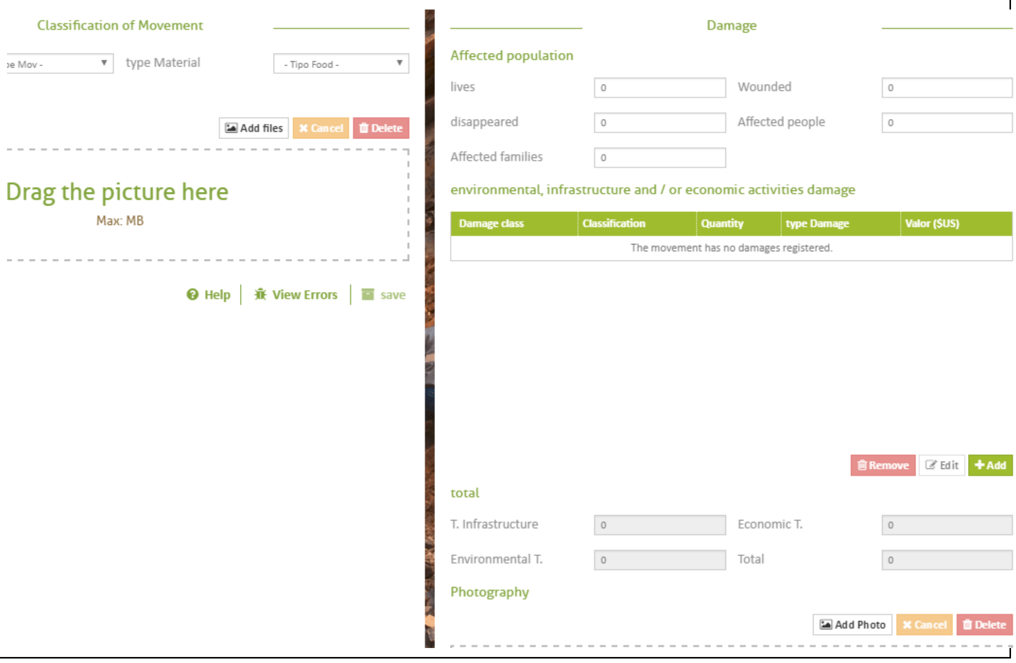
A. Entring Basic information into the system such as user profile name, email. Location of the landslide, date and time of the event.



B. Next step is the entring the information about type of landslide users may not be familiar with terms but they could enter description of the event in their local language. People can also upload photographs related to the landslide event.



C. Final step is the input of damage information related to life of people can be put by the user. User can alos add photos of the damage.



After public reporting information will be stored in temporary database. There could be many false information entered by people so later data will be checked by landslide expert at District level. After verifying information expert can input polygon data of landslides if detail information is available to them otherwise he will put point data to final database.

6.7.2. Mandatory organisational reporting

Governmental organisations like DSCWM, DMG and DWIDM will be the key organisations who works in the field of landslides. There are experts who study landslides at the field level. After the development of NELIS officers from organisations should be given trianing regarding use of system and how they could manage the information from different sources to put as input. Experts can also put bulk data directly to the system, it can be point or polygon data. If a landslide is mapped by one expert than it will automatically uploaded to the system and another expert from other organisation can see that particular landsldie have already been mapped and he could add some information to it if need.

6.7.3. Reactivation of landslides

The problem related to reactivation of landslides especially for deepseated landslides like Mulkharka and Ramche landslides in Rasuwa district. Different landslide polygon with different landslide IDs and attributes can be used to avoid overlapping of landslides. If user query data for a period of past four years then he can get all reactivated landslide data directly in the system with effective date and location.

6.7.4. Querying of landslide data

Users can get information about landslide hazard in their surrounding directly from the system. As shown in Figure 6.9 users can query data about landslides in a certain time range for particular place.

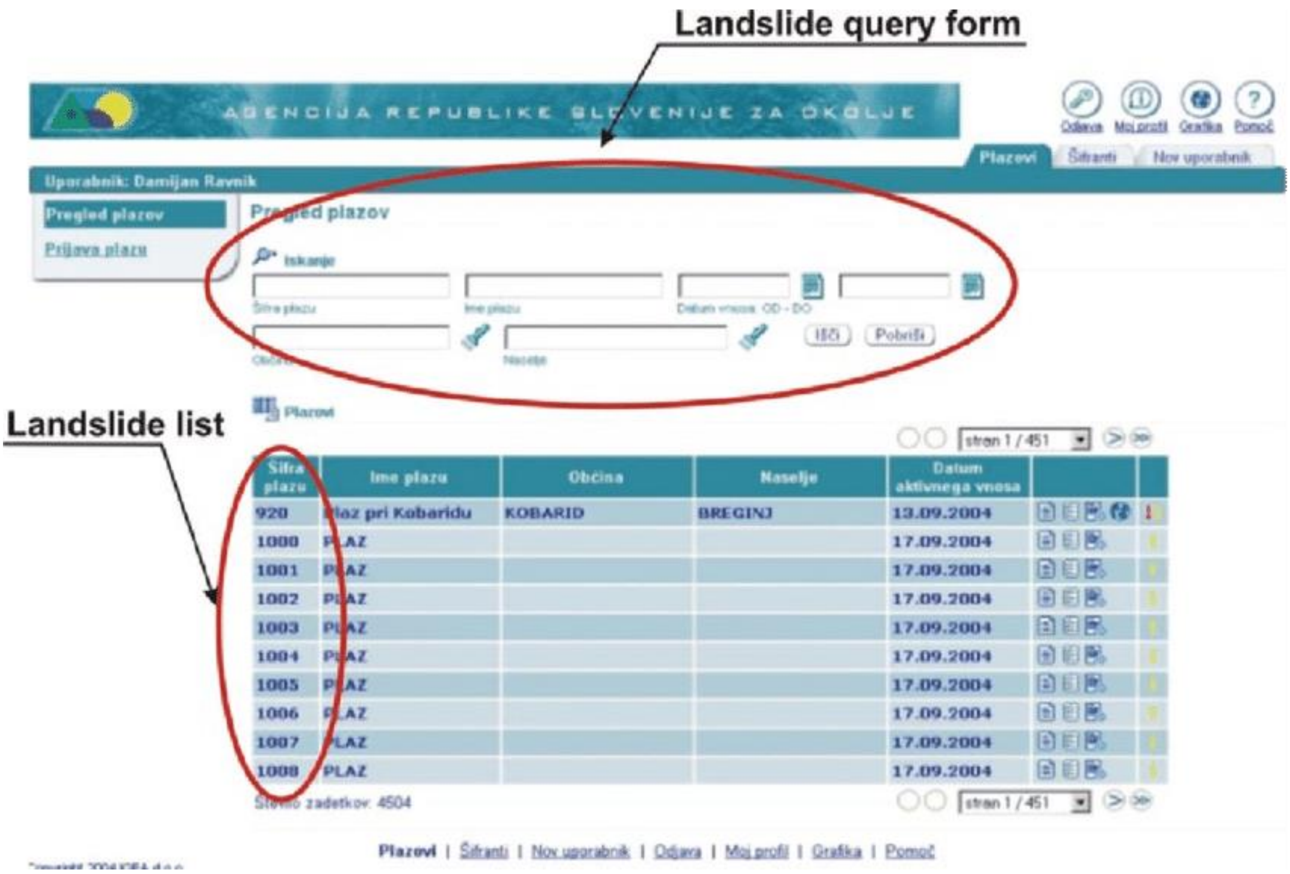


Figure 6.9 Querying landslide data from the system.(Komac & Hribernik 2015)

7. CONCLUSIONS AND RECOMMENDATIONS

In this work, several landslide mapping methods were analysed. There have already been used many techniques in Nepal for mapping landslides which range from the use of high-resolution satellite imagery to field-based investigations and use of helicopter flights. However, the objective of this work was to propose the most suitable ones for landslide mapping and to compare different inventories resulting from various techniques, to identify mismatches and reasons of inconsistency between them.

Just after the Gorkha event, cloud coverage made proper landslide mapping by satellite images difficult, so alternatives at field level were looked for. We used Tablet PC in field survey to map landslides after the 2016 monsoon. A standard tablet was used, that runs Windows operating system, as ArcGIS is not compatible with Android operating systems. 94 landslides were mapped in this way, that were extended after the monsoon or were entirely new. Readability on tablet PC was an issue during field work due to the bright sunlight, which can be overcome using special tablets for field applications. We concluded that the use of tablet-based GIS has a great potential for mapping landslides in the field directly by experts, as by organisations like DSCWM and DMG, in Nepal. There is a need to integrate the field investigations to the tablet GIS platform, and then experts can directly upload the collected data to the connected NELIS (Nepalese Landslide Information System) platform when they are connected to the internet, it makes it time efficient and effective tool to map landslides directly in the field.

In steep slopes as those of Nepal and after the occurrence of landslide events, many areas remain inaccessible. In those cases, the use of UAV can facilitate the coverage of an area with high-resolution images and videos. In this study, we investigate the usability of UAV in the field to map landslides, especially for not accessible regions. However, in Nepal UAV flights require Governmental permission and lengthy bureaucratic procedures (especially for foreign research groups) thus restricting their use. Additionally, strong winds and power limitations restrict flight operation and duration, and accordingly the collection of data of wide coverage.

The involvement of the local community is one of the important aspects for mapping the landslides and understanding its social and economic impact, and it is feasible in the context of Nepal. After a landslide event, there could be damage to houses, cattle, road network and other infrastructure that affects the life of people at the local level. There were many villages in the study area that have been fully abandoned after the earthquake and people were evacuated from these villages due to future threats of slope failures. Interaction with local community people gives more insight into their local environment and what happen just after the event. Residents can give details about the landslides that happened near their village areas, their location, time of occurrence and damage, and how they managed to sustain after the quake. Interaction with local community can take place, among others, through schools.

The frequency-area distribution was analysed for the commonly cropped area for four different inventories in the study area, to identify the criteria and to check the level of quality and completeness of the inventories for the same area. Results show that there is a difference in mapped landslide polygons regarding total area covered and delineation. These factors are based on personal user perception regarding mapping landslides. The most common sources of mismatch and error are the result of sources of error like amalgamation of smaller landslides into larger landslides. Another analysis was carried out for wider Gorkha event landslide inventories. Six landslide inventories were analysed to compare the frequency density of the landslides. The results showed that high landslide density is concentrated near the epicentral region of Gorkha district. Districts like Sindhupalchok and dholaka also shows high landslide density.

Several international organisations are working on the landslide studies in Nepal especially since the 2015 Gorkha earthquake still, the reconstruction phase is not completed in Nepal. There are many guidelines, and reports have been prepared related to landslide mapping and their uses for hazard mitigation at various levels. Currently, many Governmental organisations are working on landslides in Nepal like DSCWM, DMG, DWIDM which makes the landslide inventories based on their departmental needs. The collaboration between them would enhance the exchange of information and effective landslide hazard mitigation. This work identified the potential landslide data providers in the country and what information is available to them and how they contribute to the development of NELIS. An ideal landslide information system would involve the transfer of the information directly to the system and the user community of NELIS. In such way data about the location, time and damage caused by an event would be made available to the users requiring it.

Based on the identification of stakeholders and providers of the system and of their needs a conceptual framework was prepared. The main steps that the system includes are Identification of stakeholders, Reporting of landslides at public and mandatory governmental level, setup of the database and then delivering data to the users.

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