THE ROLE OF LANDSLIDES ON THE SEDIMENT BUDGET IN UPPER PHEWA LAKE WATERSHED, WESTERN NEPAL

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May, 2016

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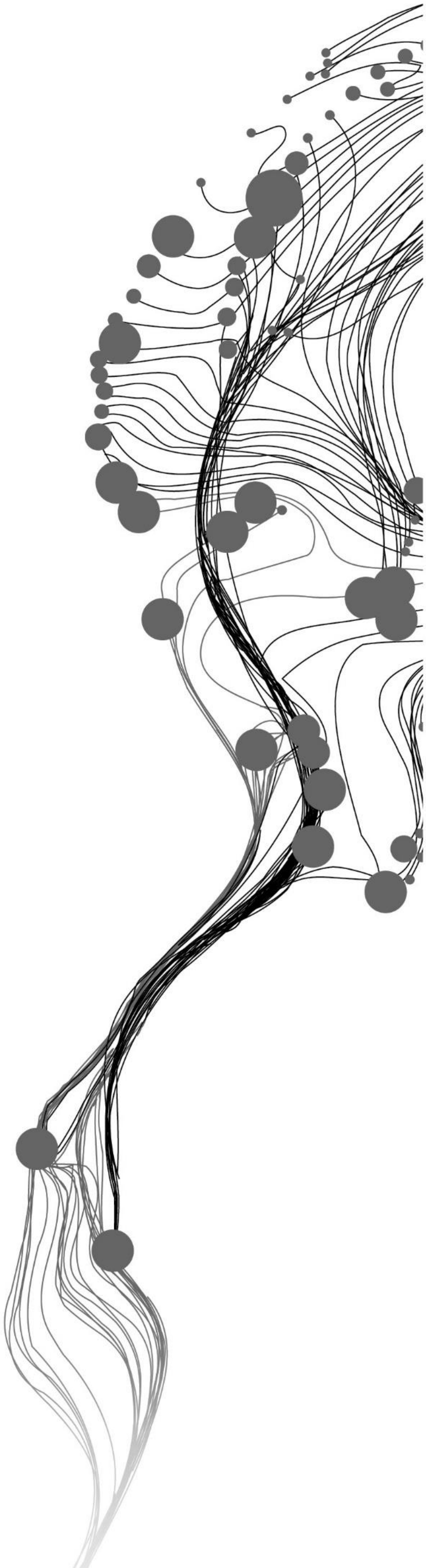

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SUSMITA DHAKAL
Enschede, The Netherlands, March, 2016

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.
Specialization: Applied Earth Sciences – Natural Hazards and Disaster Risk Management (AES-NHSRM)

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Dedicated to all victims affected by natural disasters during 2014 and 2015 in Nepal

ABSTRACT

Regular water erosion is a constant process that contribute to the catchment's sediment flux in yearly basis. Landslides, on the other hand, are the events triggered by distinct phenomenon such as extreme rainfall. And consequent sediment supply to the fluvial system is a concern of downstream population. Phewa Lake at the outlet of its draining valley has been forced to receive sediment load from the upstream part of the watershed. Siltation in this lake by normal water erosion process is an issue that has been raised for years. Additionally, the mass movement event occurred on 31 July 2015 added considerably high sediment turning the lake murky.

This study mainly concentrates on the question how - landslides contribute to the total sediment budget in upper Phewa Lake watershed, taking a case of the upper north-western Andherikhola sub-basin which provides recent examples of large debris flows, and landslides that fed the river system in 2015.

Two main methodological approaches i.e. baseline erosion estimation and sediment delivery assessment that is contributed by landsides were considered. The research has estimated normal sedimentation rate in pre landslide situation i.e. for the year 2014 and also for the year of disaster 2015 by applying Revised Morgan Morgan Finney daily erosion model in PCRater GIS platform. And four different approaches: 'planar areal segment', 'triangular prism', 'parabolic segment', and 'rectangular prism' were applied to reconstruct landslides volume including the added deposit into the river system and the estimation completely relied on field data.

With a number of adaptations such as application of separate equations for sand, silt and clay, introduction of a new code to enhance the role of saturated hydraulic conductivity i.e. initial infiltration base followed by runoff calculation as a rainfall fraction, increment of effective hydrologic height, slope correction for terraced cultivation areas, and cloud correction in NDVI images, the sediment flux for 2014 and 2015 were estimated as 51013 and 66383 tons with the average rate of 16 and 17 tons/ha/y. This result has shown close agreement to past studies in the area and in catchments of similar environmental settings. The aforementioned second and third approaches of debris volume reconstruction have provided better estimation to debris flows with long runouts and first approach has given relatively good estimation for shallow and complex landsides. With selected approaches the total volume of debris directly deposited into the river was estimated between 871858 and 1119792 m^3 and the finer constituents was 337731 m^3. This finer constituents of sediment is 9 times and 7 times higher than sediment yield by RMMF-D erosion simulation for 2014 and 2015 respectively. The net contribution by landslides including incremental volume of erosional sediment yield in 2015 was estimated at 338482 cubic meters.

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1. INTRODUCTION

1.1. Background

On 30 July 2015, after a torrential rainfall event, typical for the monsoon period in Nepal, three large landslides (debris flow) in three different villages – Badaure tamangi, Dikhur pokhari and Kaskikot- killed 29 people, damaged many buildings and properties, and disrupted a road in the upstream part of the Phewa Lake watershed (BBCNews, 30 July 2015a). Moreover, the Phewa lake itself turned complete murky just after receiving flood water and sediments by its inlet river - Harpan Khola (The kathmandupost, 3 Aug 2015). It is claimed that the recent landslides in the upstream area are the main cause of this massive sedimentation in the lake (Republica, 6 Aug 2015).

Phewa Lake watershed is constantly facing natural hazards like landslides, soil erosion, upstream and downstream sedimentation as a common process. Every year, especially during monsoon, slope failures occur in this region in western Nepal (Dahal and Hasegawa, 2008). The fragile lesser Himalayan Meta sedimentary geological setting with many discontinuities in rock strata (e.g. folding, faulting) (Monique, 2010), intense monsoonal rainfall (Rowbotham and Dudycha, 1998) and forest degradation, rural road construction, rapid change of land uses and other human activities (Regmi and Saha, 2015) are responsible for the multi-hazards in a cascading manner.

Since Nepal is located in an active seismic zone, earthquakes and associated landslides are inevitable. The recent earthquake of 7.8 magnitude that shook central Nepal on 25 April 2015 was followed by many aftershocks (USGS, 2015). It had triggered more than 3000 landslides (ICIMOD, 2015), 4312 (Universieit Utrecht, 2015). It was found that the landslide concentration mainly extended towards the east from the epicentre, by reason of the eastward- directed fault rupture of shocks (Collins and Jibson, 2015). But seismologists now also warn for a probable large earthquake in the western part of the country because of high energy trapped underneath is yet to be released (BBCNews, 7 Aug 2015b). This is also a warning for a possible increase in landslide occurrence in the Phewa watershed that is located in the southwestern edge of Pokhara valley, western Nepal.

The Pokhara Valley receives the highest amount of annual rainfall (Average annual rainfall from 1971- 1993 ranges from 3829 mm to 5216 mm in lower and upper edge of the Phewa Lake watershed, Rowbotham and Dudycha, 1998) in the country, as a result of the strong orographic effect of Annapurna Himalayan range (Dahal and Hasegawa, 2008). A study carried out by Basnet et al. (2012) in two villages in the upstream part of the watershed found a landslide density of 0.44/km², with 51% of the landslide area in agricultural lands and 33% in forests. This landslide density may increase with the increased annual amount of precipitation and also with intense rainfall events that are possible because of climatic change (GoN, 2010).

Regular water erosion process is a constant phenomenon that contribute sedimentation downstream. Certain rate of erosion has accepted by locals as minimal loss (threshold for Nepal is 10-20 tons/ha/y according to Laban (1978) as cited in Fleming, 1985) because they are aware of the characteristics (rugged topography, steep slope: average slopes above 40%, elevation range from about 800 to 2500 masl, and seasonal intense rainfall) of the location where they have been residing for generations. But when problems related with increased rate of erosion visualized, studies had begun to quantify the rate at plot level (Fleming, 1985), and also at watershed scale (Bhandari et al., 2015).

1.2. Erosion modelling

Globally, erosion has studied using indirect proxies (e.g. suspended sediments in rivers); empirical, conceptual, and physically based predictive models. The erosion models differ the inferences on which they stand (conceptualized, empirical, and physics based), scale (spatial/temporal) they consider, process they model, data they require, and how parameters and area are dealt. The erosion modelling evolved with Universal Soil Loss Equation (USLE) in 1970s which was established by regression equations based on hillslope observations. Later, advancement came applying grid or cellular approach. Areal Non-point Source Watershed Environmental Response Simulation (ANSWERS) is a pioneer of this type that adapted some empiricism and modelled events originally, updated later as a continuous simulation (Morgan, 2011). Water Erosion Prediction Project (WEPP), European Soil Erosion Model (EUROSEM), Griffith University Erosion System Template (GUEST), Chemical runoff and Erosion from Agricultural Management System (CREAMS), and The Limberg Soil Erosion Model (LISEM) are few examples of physically based erosion and sediment transport models (Merritt et al., 2003). The intermediary models such as Agricultural NonPoint Source (AGNPS) are conceptual models which consider the erosion, sediment transportation, and deposition processes with hypothesis that govern system behaviour (Merritt et al., 2003; Aksoy and Kavvas, 2005)but not follow exact physical rules. The erosion and sediment transport models have specific application. For instance, some of them are applicable for plot or hillslope (e.g. USLE) or catchment (Morgan - Morgan – Finney, MMF) at annual time step, and others such as EUROSEM, and LISEM are event based models. Whereas WEPP is a continuous simulation type (Merritt et al., 2003). The physically based predictive models have been used extensively, their complexity and distributive nature, however require many different parameters as input (Wasige, 2013). Whereas, empirical models, eg. USLE family and conceptual models such as MMF are simple lumped models (need less input data) equally perform well like complex distributed models (Jetten et al., 2003).

1.3. Landslides and sediment delivery

According to Korup (2005) assessing the influence of landslide on total sediment budget, and the predictive modelling of landslide-induced sediment delivery and routing is a challenge in catchment scale studies. For instance, in a small catchment scale study in Central Switzerland, Schuerch et al. (2006) had estimated volume of shallow landslides by multiplication of surface velocity of moving mass, thickness of sliding plain above the failure plain, and stream-wise width of landslide mass. Next, after quantifying the proportion of sediment injected into a stream, they applied a geophone to quantify sediment transport by the channel. Whereas, the common empirical approaches that applied for the estimation of landslide runout distance and proportion of materials reached to the channel are **'frequency-area'** and **'volume-area'** relationships (Tsai et al., 2013) and 'mass-change' method. In case of analytical methods, different formulations based on lumped mass approach are included, e.g. sled model. Whereas, numerical methods use continuum fluid mechanics models which are guided by the conservation equations of mass, momentum and energy. Dynamic models such as MADFLOW, Rapid Mass Movement System (RAMMS), MassMov2D and Dynamic analysis of Landslides in three dimensions (DAN3D) are under this category (Luna et al., 2012; Hussin, 2011). Process based model such as Hydrological Simulation Program-FORTRAN (HSPF), and SHETRAN are few models in use to estimate sediment transportation and yield that has also backed by shallow landslides (Tsai et al., 2013; Bathurst et al., 2005).

1.4. Problem statement

Phewa Lake has national as well as local importance because of its rich biodiversity, proximity to the Pokhara city, and significance for socioeconomic prosperity (fisheries, recreation, tourism, irrigation, hydropower and spiritual faith). However, the lake has been suffering from continuous sedimentation from rural and urban sub watersheds. According to Pokharel (2008), the area of the lake has reduced from 10 km^2 in 1957 to 5.5 km^2 in 1976 and to 4.4 km^2 in 1998 with the shrinkage rate of 2 ha/yr, and this decline was blamed

to sediment load from upstream parts. It is assumed that the high amount of sediment intake during past big landslide events is one of the causes for lake area reduction (FEED Nepal P Ltd., 2014).
So far research in the area has mainly focused on linkage between erosion, land cover and land use, land conservation practices, and few on sedimentation. In early years of erosion studies, degradation of forest and most importantly grasslands were reported as major causes of soil erosion in the watershed (e.g. Fleming, 1985; Impat, 1980). In a recent study, the effect of socioeconomic activities on soil erosion has also emphasized (Bhandari et al., 2015). The sedimentation studies that has conducted to date are using suspended load in river water as proxy (Ross and Gilbert, 1999; FEED Nepal P Ltd., 2014), and field measurements particularly in silt trap area of Harpan delta (Sthapit and Balla, 1998).
The studies about linkages between landslide occurrences and the sediment production not only rare in Phewa catchment but also are few in Nepal Himalaya. After a continuous monitoring of time series analysis of a single landslide (0.5 km^2) for 46 years, Gallo and Lavé (2014) recommended landslide induced erosion to be taken into account while measuring fluvial suspended load. The contribution of landslides on the fluvial sedimentation in Nepalese mountains is also reported by Gabet et al. (2004). Shallow mass movements in deeply weathered zone around rock faults are the dominant feeders, approximately 90% of total sediments that has come from mass wasting phenomena in Phewa watershed (Ramsay, 1987). On the contrary, Khanal and Regmi (2015) has mentioned that the big landslides are the source of sedimentation in the basin. But the research-based insight is missing regarding the role of landslides on sediment budget.
This study mainly concentrates on the question how - landslides contribute to the total sediment budget in upper Phewa Lake watershed, taking a case of the upper north-western Andherikhola sub-basin which provides recent examples of large debris flows, and landslides that fed the river system in 2015. **Revised MMF erosion model** adapted in daily time step (Shrestha and Jetten, 2016) coupling with 'area-depth' method for debris volume estimation will be implemented in PCRaster platform (details in section 3.7).

1.5. Research objectives

The main objective of this study is to assess the contribution of landslides to the sediment load entering the fluvial system in the upper Phewa Lake – Andherikhola – watershed. The specific objectives and associated research questions are defined as:

1. To estimate the baseline sedimentation rate (daily and annual) by water erosion processes.
    - *Which elements of the RMMF erosion model have to be adapted to the Himalayan environment?*
    - *What is the spatial extent for the distribution of sediment deposits within the catchment in normal years (without extreme rainfall)?*
    - *What is the soil loss from the catchment in years without debris flows?*
2. To reconstruct the spatial runout extent and sediment delivered to the fluvial system from selected landslide and debris flow incidences in 2015.
    - *What is the extent of debris flow runout path that has reached the river network?*
    - *What is the volume of earth materials that was initially released?*
    - *What is the volume of debris that was injected to the river?*
3. To estimate the incremental sediment delivery to the river system that is not comparable with normal sedimentation rate.
    - *What is the incremental erosion rate in 2015 compare to the normal sedimentation rate of the year 2014?*
    - *What is the net additional sediment from landslides to the fluvial system?*

Working hypothesis and assumption:

Landslides and debris flows, triggered by extreme rainfall, contribute considerably more sediment to the river system than erosion by runoff and splash as a result of the same rainfall.

1.6. Conceptual framework of sedimentation in the phewa lake watershed

The conceptual framework that is presented in Figure 1-1 explains the general sediment distribution inside the Phewa Lake watershed. It may however, differ in south and north flowing sub watersheds (Figure 2-1).The debris flows from these basins can directly reach to the lake instead of entering through the river network. Water erosion during and post rainfall events is a regular contributing phenomenon for the sediment distribution within the catchment. Soil detachment by splash, sheet and rill erosion on hillslope, transportation of that sediment by runoff in gullies and small streams, leaving the heavy sediments as 'hillslope storage' and eroding soils particularly along their flowing paths which ultimately enter to the bigger channel are the major erosional processes. Similarly, shallow as well as deep seated mass movements that either deposit onto the hillslope or be injected to the river system are the fundamental but not very frequent processes which supply high amount of debris.

The deposit onto the upslope further goes in hillslope erosional phase while the sediment entered as a huge mass into the fluvial system undergo river flow erosion and transportation sequence. The terrain features such as slope, aspect, and landforms, land cover and land use practices including rural road construction, parent materials, regolith condition, and importantly rainfall amount, duration and intensity affect how rapid would be the hillslope sediment loss and siltation downstream.

Finally, the material received by channel network flows downstream either as suspended or bed load depending on the texture of material and stream power of river discharge. Scouring of riverbed, and undercutting the river terraces in one hand increase the sediment load, and enhances channel deposits on the other hand. The down channel movement of materials is in sequential order inside the Phewa fluvial system known as 'channel conveyance', which terminates endowing suspended load to the lake.

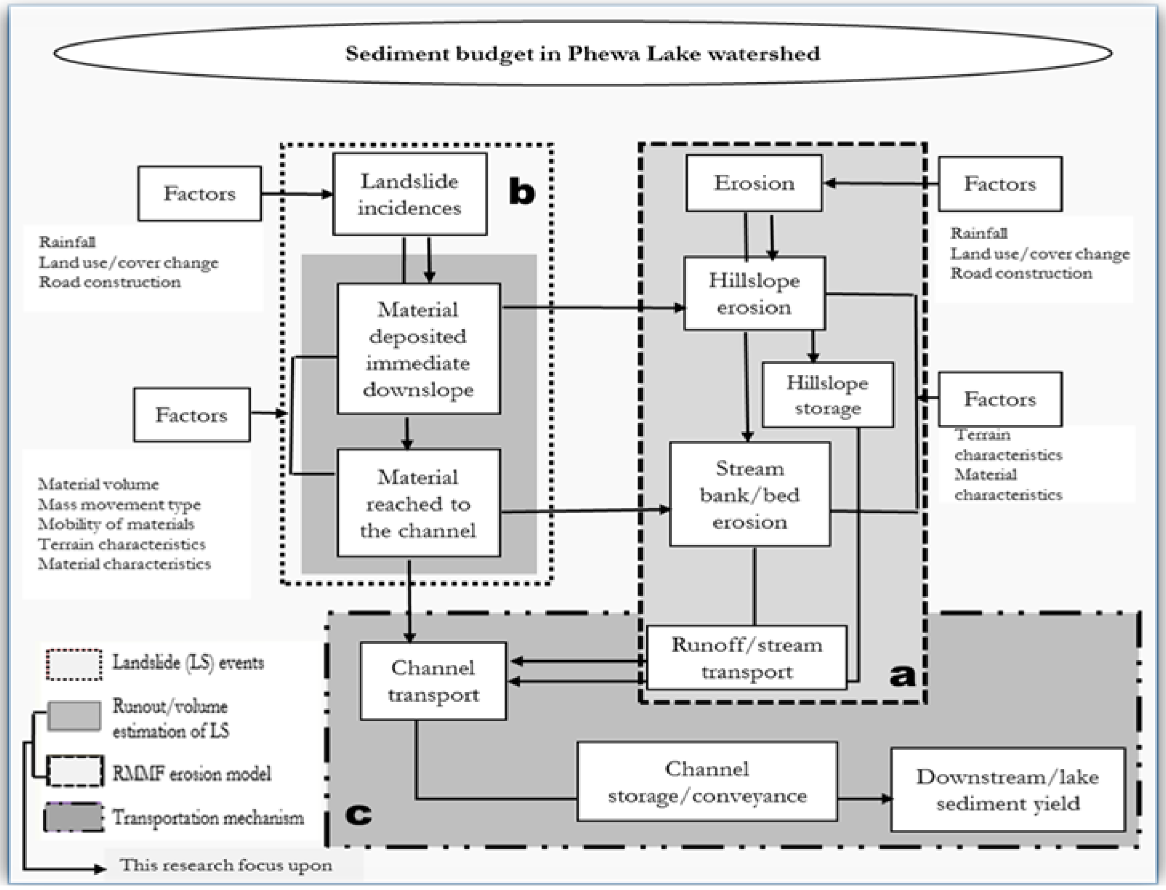


Figure 1-1: : Conceptual framework of sediment budget in Phewa Lake watershed depicting (a) regular water erosion, including hillslope storage and runoff transport (b) sediment contribution by landslides, (c) channel sediment transport that received by erosion and mass movement processes and storage on the channel itself.

2. STUDY AREA

2.1. Location and general discription

Phewa Lake is the second largest lake in the country. It was initially formed by damming Seti river system in western Nepal by a gigantic debris flow centuries back (Monique, 2010), and is now semi natural landform with a dam in the outlet (Figure 2-1). About 60% area of the Phewa watershed has steep slope (>20⁰) (GoN, 1985a).

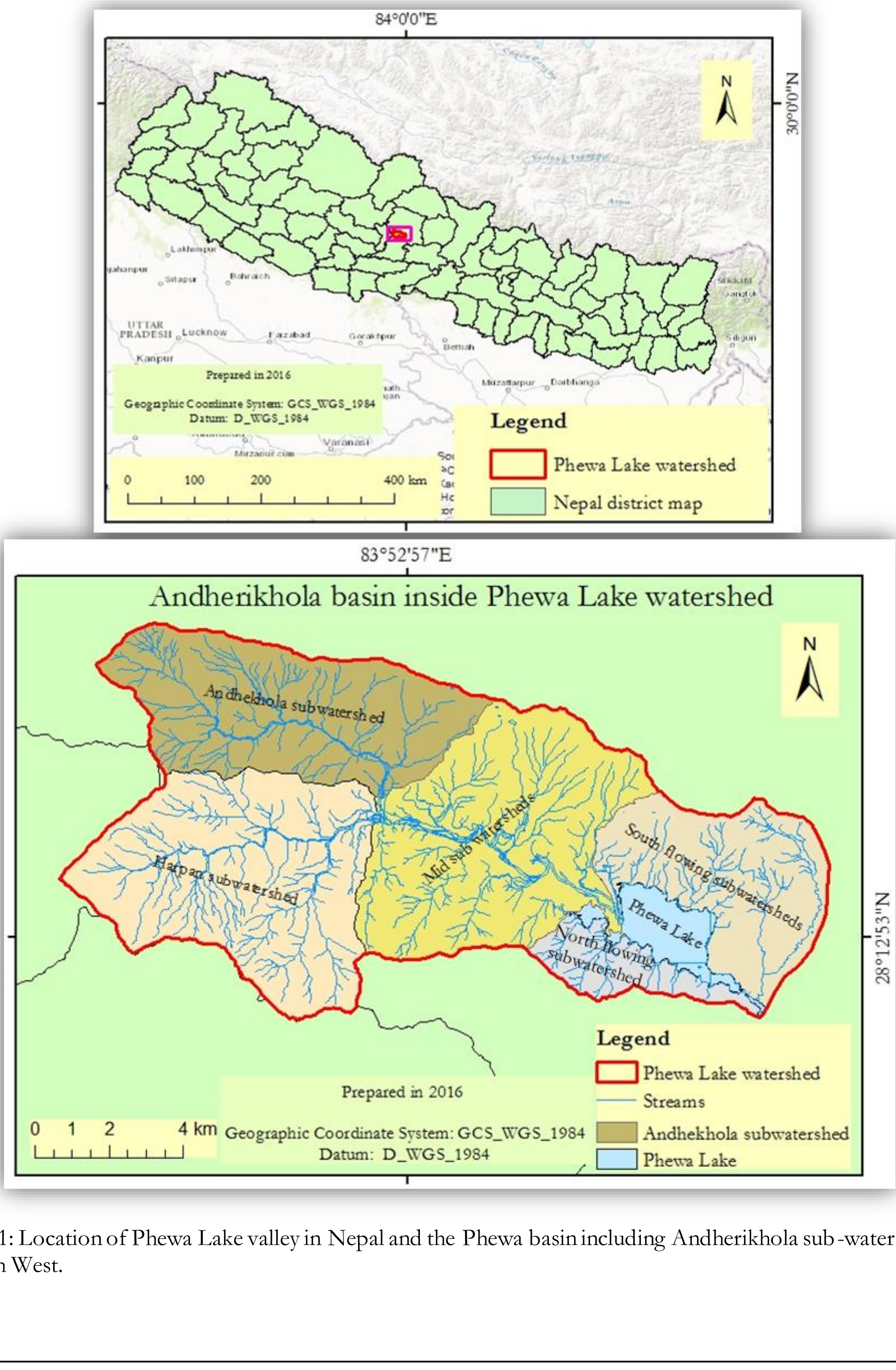


Figure 2-1: Location of Phewa Lake valley in Nepal and the Phewa basin including Andherikhola sub-watershed in the North West.

Aherikhola basin is located inside the Phewa watershed at north western part extending 28⁰14'53''to 28⁰17'25''latitude to 83⁰48'26''to 83⁰ 54'16'' longitude in western Nepal (Figure 2-1). It covers 27 km^2 area and stretched from valley floor (819 msl) to the highest peak of 'Lwasepakha raniban' (2064 msl). Most of the south facing slope in the north is cultivated and settlements are denser with dominant slope angle of <30⁰ whereas, in north facing slope in southern part dense forest is abundant with dominant slope angle of >30⁰ (Figure 2-2) Andherikhola is of 8th order river system with flow accumulation towards northeast and mixes with Harpan khola downstream (Figure 2-1).

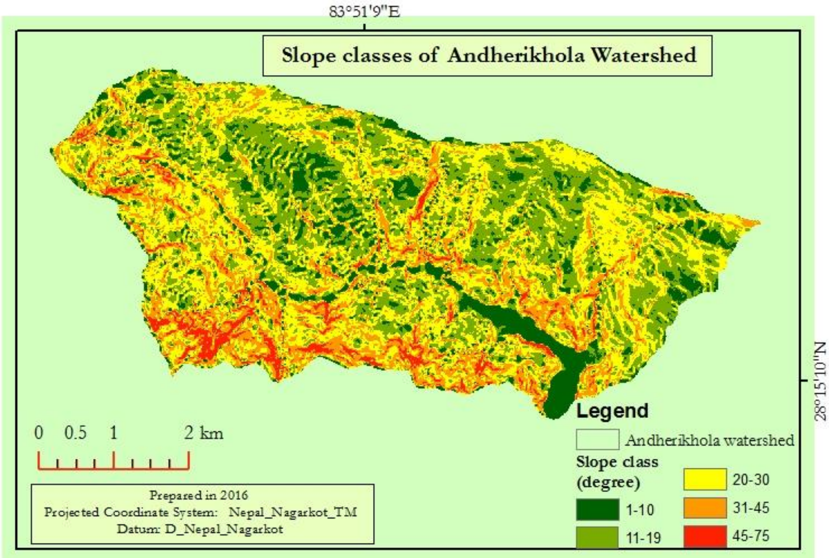


Figure 2-2: Slope class distribution (1 to 75 degree) of Andherikhola basin.

2.2. Climate and rainfall

Climate of the watershed is monsoonal (humid) tropical to sub-tropical. As illustrated in Figure 2-3, it is located in the highest rainfall zone of the country. The mean annual rainfall is 4080 and 3810 mm for 'Bhadaure Deaurali' and 'Pokhara Airport' stations respectively and almost 82% of total rainfall occurs during monsoon (1985-2015).

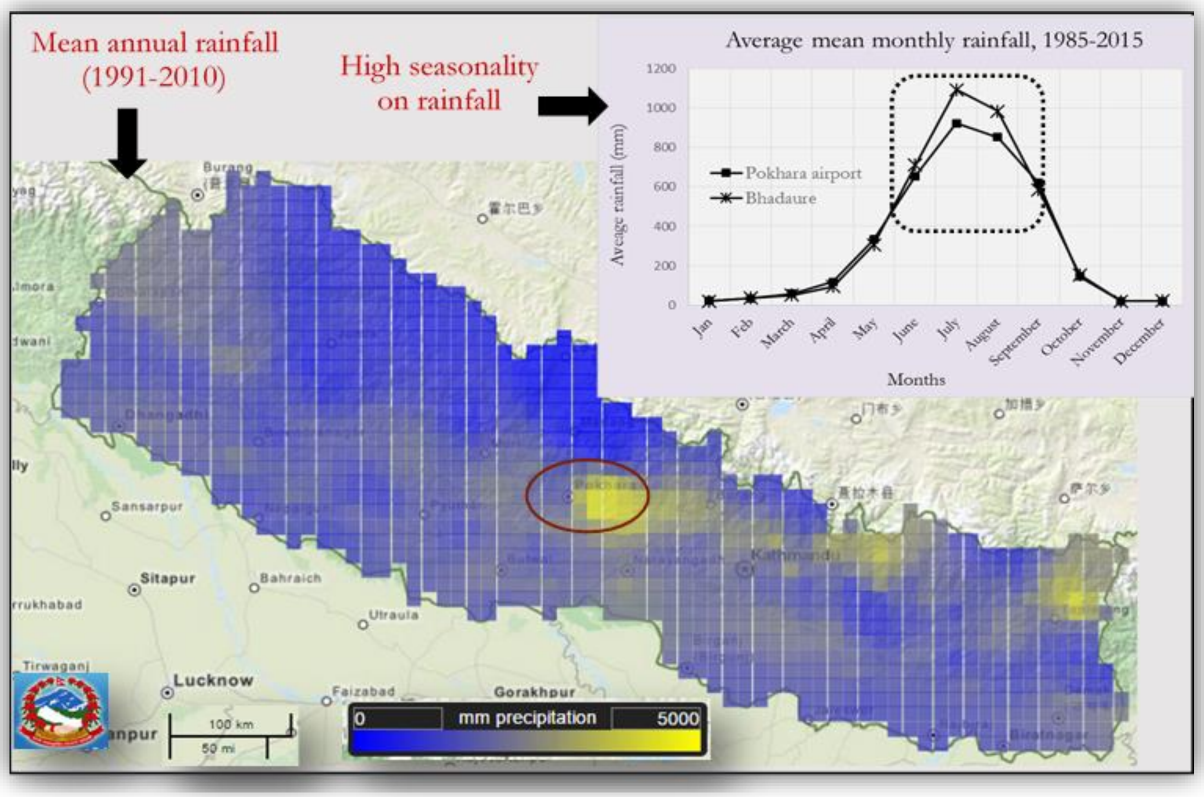


Figure 2-3: Average annual rainfall distribution of Nepal highlighting the highest rainfall receiving part where study area lies and a chart presenting the dominancy of seasonal rainfall pattern(GoN-DHM, 2016).

Whereas temperature lies between 5-6 ^{0}C to 14-20 ^{0}C during winter and 18-22 ^{0}C to 25-32 ^{0}C during summer (see temperature plot in Appendix 1).
Rainfall increases with the elevation showing perfect linearity if observation data are available within the same watershed (Ramsay, 1987), however because of diverse microclimatic condition the pattern is not visible if data mixed from different valleys (Description in section 4.2). 'Gumble distribution' analysis (1985-1914) shows the return period of 300 mm rain is of 15 years and 'intensity duration frequency'- IDF curves analysis shows if the duration of rain event of 30th July 2015 (315.3 mm) taken as 24 hours, 12 hours, and 8 hours, the return period will be of 10, 50, and 100 years for the station Bhadaure deaurali (see gumble distribution charts and IDF curves in Appendix 2 &3).

2.3. Erosion and landslides situation

As mentioned earlier, Andherikhola watershed receives high rainfall, lies in moderately steep to steep slopes as well. In addition, it also has weak geological setting. The basin comprises of two main lithological units that extend from east to west strike and dip 25^0 to 70^0 aligning with local topography. In the northern side of the watershed grey to dark grey phyllite is dominant which is intercalated with white to grey metasandstone. The southern part of the watershed consists of fractured, coarse white quartzite containing clear ripple marks with medium to thick depth (GoN, 1985b). A combined effect causes erosion and landslides especially in rainy months.

2.3.1. Erosion status

As stated in section 1.1, minimal soil loss is acceptable in the locality. To maintain soil profile people has their own traditional knowledge such as terrace farming (slopping or level terraces), and keeping the forest area in steep slopes, and onto the summit of the peaks in gentler hillslopes (Figure 2-4). But measurement of erosion rate is hard for locals. Studies on hillslope soil loss begun in 1970s. Mulder (1978), in a study with collaboration to government of Nepal, reported soil loss of 9.4 and 34.7 tons/ha/y from pasture and overgrazed grassland by field plot method at about 25^0 south facing hillslope. Similarly, erosion rate at Banpale village in Andherikhola, and the sediment load at 2 km upstream (Chankapur) of Phewa lake had estimated by Impat (1980) as 30.75 tons/ha/y and 9.94 tons/ha/y respectively.

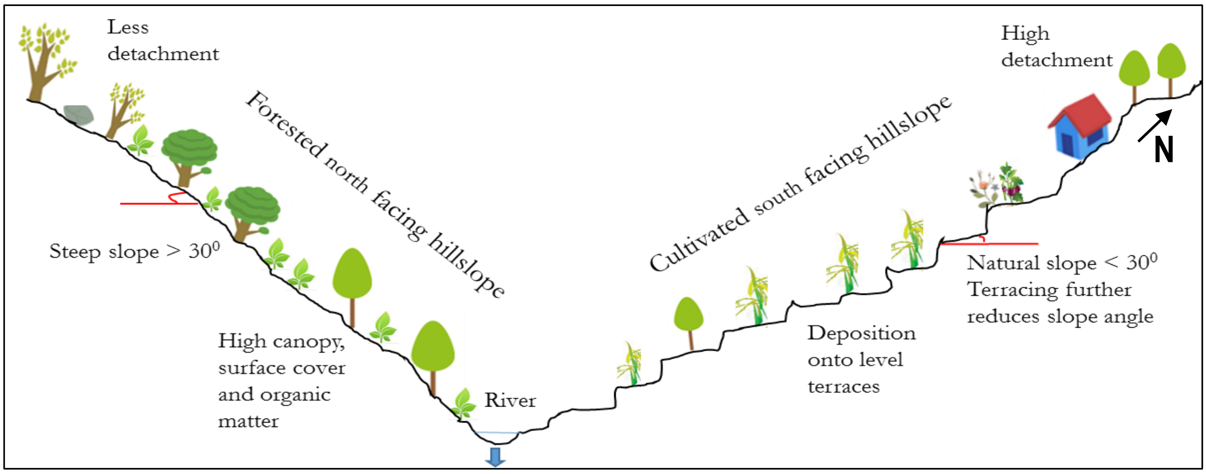


Figure 2-4: Schematic diagram of typical erosional process in Andherikhola watershed.

Most of the studies have been done taking the entire Phewa approach, putting focus on inlet and lower watersheds (e.g. Ross and Gilbert, 1999; Fleming 1985). While doing so, Andherikhola watershed was not considered as a high sediment contributing catchment. However, a recent research has warned the constant increment of sediment loading from this basin – average soil loss 22.5 (1995), 27.6 (2000), 28.8 (2010) and predicted 38.8 tons/ha/y – for the year 2015 (Regmi and Saha, 2015).

2.3.2. Landslides occurrences

The natural terrain on hillslopes within watershed show the evidences of past history of shallow as well as deep seated landsliding (Figure 2-5 **&** Figure 2-6). According to Ramsay (1985), common mass movements in Phewa Lake watershed are "translational failures" or "debris slides", which are further categorized as "failure on slopes of <36^0 in unusually weaker or disturbed materials", "failures on a stream and river banks due to undercutting", and "failure on undisturbed regolith with sufficient runout to a channel to allow the formation of flow in the displaced material" (landslide map in Appendix 4). FEED Nepal P Ltd. (2014),

Figure 2-5: Evidences of past large landslides near Thulachaur debris flow (Southern slope).

had explained that the watershed is characterised by enormous debris flows in north western part in Paudur and Bhirmuni areas, where many slides were observed during field visit, too. The reason behind that they have mentioned are "thick soil, sparse vegetation, and very small drainage length" including human interventions, mainly haphazard road construction. Another past study made by Tamura (1996) in two villages of Kaskikot (northern slope near the outlet of Andherikhola) had shown the farming practices especially terraced paddy cultivation in very shallow (<30 cm) soil on bedrock slope enhanced shallow failure (Samili village), and cracks had noticed developing in deposits of previous deep seated landslides, which author had taken a sign of activated creeping that can be catalysed by drainage of irrigating water in paddy fields.

Though rural roads are taken as a cause of incremental mass movement in recent years (Devkota et al., 2015) , landslides of 2015 has occurred mostly on forested north & south and south western part, few of them are included in this research.

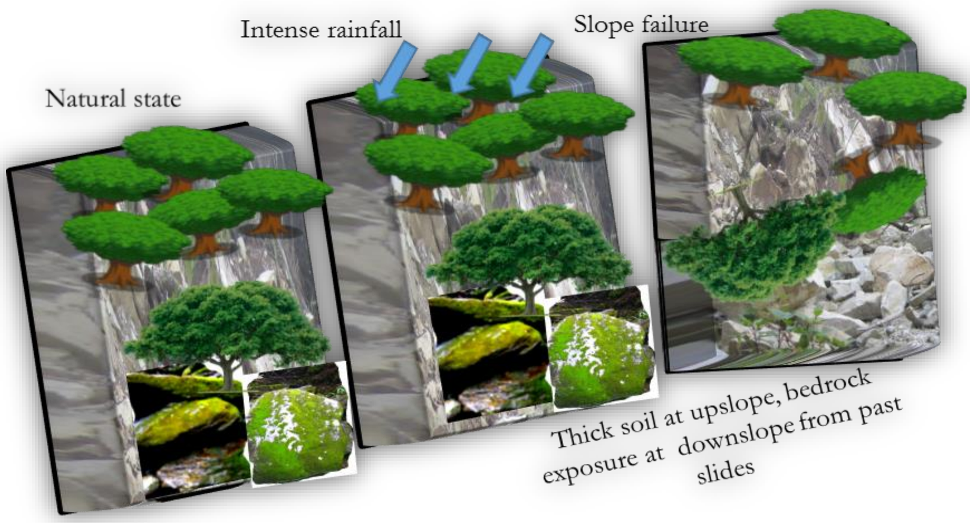


Figure 2-6: Schematic diagram of landsliding (Ratopahiro) at the source zone of Andherikhola.

3. MATERIALS AND METHODS

3.1. Methodological approach

This research has three main methodological units to address its aim which includes baseline erosion estimation, sediment delivery assessment that is contributed by landsides, and comparison of both processes in terms of sediment loading to fluvial system. Ancillary data review (pre-field visit) and preparation afterwards are taken as **complementary part** as illustrated in Figure 3-1. The **first unit** deals with the data collection and preparation for the baseline erosion estimation i.e. of the year 2014. The **second unit** is for the material addition by landslides to the river network taking the case of debris flows occurred in 2015. The **last one** is the modelling of the sedimentation flux for both distinctly different datasets (normal erosion, and landslides situations) separately, meaning erosion model runs twice. This part also consists the comparison of both phenomenon in terms of sediment filling to the streams. This chapter describes all the methods applied to collect and prepare the data, and also the simulation of spatial sediment distribution. For simulation, Revised Morgan Morgan Finney-RMMF erosion model (see explanation in **Section 3.7**) was chosen and implemented in PCRaster platform.

3.2. Ancillary datasets

The secondary data viz. digital topographic map (1992) of 1:25,000 prepared from aerial photos including contour lines of 20 meter apart, baseline soil map of 1: 50,000, daily rainfall and temperature data of nearby meteorological stations, satellite image of 2013 of 2 m resolution, google image of 2014, satellite image of 2015 with 4.8 m resolution and normalized difference vegetation index (NDVI) map series of eMODIS of the year 2014 and 2015 were accessed from different sources as summarized in Table 3-1 below.

Table 3-1: Major data collected from secondary sources.

Data	Year	Format	Scale/ resolution	Sources
Land system map (contains soil type & texture information)	1984	Printed copy	1:50,000	GoN-Department of Survey
Geology map		Digital vector		GoN-Department of Mine & Geology
Topographic map	1992	Digital vector	1:25,000	GoN-Department of Survey
Daily rainfall & temperature data	2014 2015	Digital excel sheet		GoN- Department of Hydroloy & Meteorology
Road network and built up data	2013	Digital vector		University of Lausanne
Pleides satellite image	2013	Digital raster	2 m	Digital globe
Google earth image	2014	Digital raster		Google earth
RapidEye satellite image	2015	Digital raster	4.8 m	
eMODIS NDVI map series	2014 2015	Digital raster	250 m	http://earthexplorer.usgs.gov/

3.3. Field data for baseline sedimentation rate estimation

Three major tasks were completed to collect data from the field including collection of undisturbed soil samples by 'core sampling' method, measurement of surface soil strength using 'pocket torvane' and collection of information about current land use practices. In-situ observation was made during 17-30 Nov 2015.

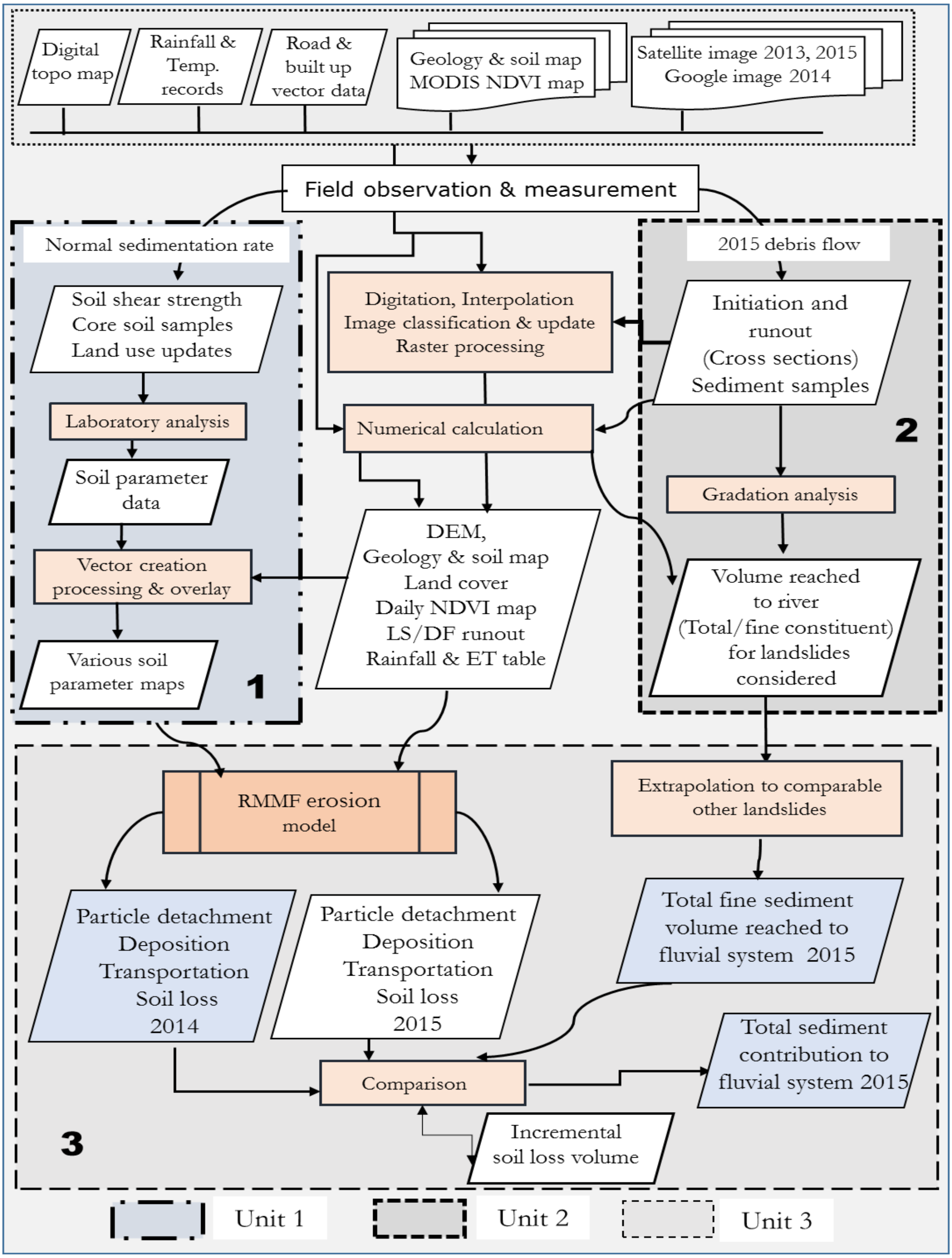


Figure 3-1: General methodological flowchart including (1) data preparation for baseline sedimentation rate by regular water erosion process - left vertical box, (2) data preparation of spatial location and landslide/debris flow deposits that reached to the river network - right vertical box, and (3) Modelling sedimentation rate using RMMF erosion model. The content in between is secondary data processing.

3.3.1. Undisturbed soil sampling

Available soil map provides less information about different soil parameters needed as inputs for RMMF. Thus, adapting methods described in Carter and Gregorich (2008), 22 undisturbed soil samples of top 5 cm surface soil were collected from different land uses and terrain units using stainless iron core of vol. 98.17 cm^3 (see spatial location map in Figure 3-2). Purposive sampling was the approach taken with three longitudinal transects covering different land uses and terrain units of the watershed. All samples with detail information – sample number, date, location, and land use – were packed in core sampler case, and transported to the Geoscience lab of Faculty of Geoinformation Science and Earth Observation (ITC), University of Twente for laboratory analysis.

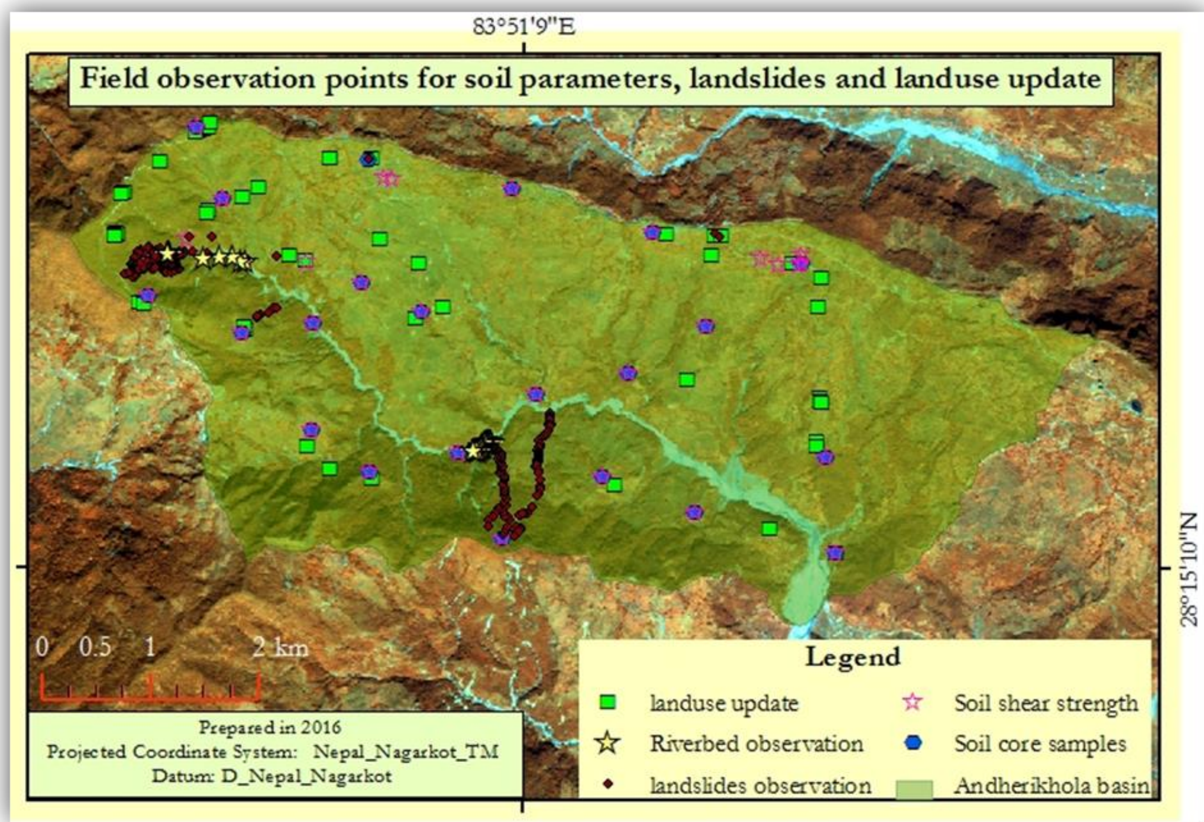


Figure 3-2: Field observations for soil shear strength (31), core sampling (22), landslide cross section (264), land use update (54), and riverbed observation (58) inside Andherikhola sub-watershed.

3.3.2. Soil cohesion measurement

Soil strength against detachment by raindrops and overland flow is fundamental in erosion and sedimentation studies. Soil which has high cohesion with certain moisture percent, fine root networks, organic matter, and textural combinations has high shear strength. In erosion studies, shear strength of soil has been taken as index of resistance to erosion. In RMMF, soil cohesion is one of the major input parameter. For this reason, field measurement of top soil shear strength was made using 'E-285 Pocket Vane Shear Tester' (Zimbone et al., 1996) in thirty one (twenty one undisturbed soil sampling points and surroundings of 10 different landslides) locations (Figure 3-2).

3.4. Field data for assessment of sediment contribution by landslides

Observations of four separate (two small and two big) debris flows, and a complex and a small landslide that ended up to the river system made in the field. The focus was to collect information about delineation of runout extent and cross section, debris volume (entered to the river) and fine sediment fraction. Laser Range Finder- LRF (Truplus 360R) was used for first two task and samples were collected for the last. Riverbed was also observed to see the sediment deposits along the flood plain.

3.4.1. Delineation of runout extent and cross section

Height, width, and length of failure plane at scar, 'slope distance' and 'cross section' in different sections of debris flow path were measured with the help of LRF. The information about parent materials, previous mass movement situation and real time experiences of locals were documented from 12 key informants (see KIs list including locals and representatives of different institutions in Appendix 5). Deposits height and cross section along the runout zone and at the toe (fan) were recorded. Photographs of scar, transportation and deposition zone that can be used for the estimation volume were taken with possible scales.

3.4.2. Estimation of sediment fraction

Since this study is focused on sediment load contribution by landslides into the fluvial system, the transportation of fine materials (<2 mm) is fundamental to enhance downstream siltation. To estimate percentage of fraction of such fine materials about 500 gram (altogether 16 samples) debris were collected in plastic samples bag with details (name of landslide, sample number, location, initial scar or transport zone, or lateral scar, or deposition specification and date) and transported for dry sieve analysis.

3.5. Laboratory analysis

The soil and sediment samples collected during field work period have been analysed in the laboratory. The fine sediment fraction of 16 sediment samples taken from different landslides/debris flows have been analyzed in Tribhuvan University - Central Department of Geology, Kathmandu. Whereas, the 22 undisturbed soil samples were brought to ITC laboratory to carry out laboratory analysis for the estimation of soil parameters - saturated hydraulic conductivity, porosity, bulk density, soil organic matter, and texture (coarse fragments, sand, silts and clay percentage) as described in section 3.5.1 (flow chart in Appendix 6-a).

3.5.1. Soil parameters analysis

The methods applied during laboratory analysis has basically adapted from Carter and Gregorich (2008), Tan (1996) and Lal and Shukla (2004), however for particular soil parameter separate literature has referred wherever needed.

Saturated hydraulic conductivity (Ksat) analysis

For the Ksat estimation the 'constant head test' method was used applying the Laboratory Permeameter - Model 1-09-02E of Eijkelkamp Company. Firstly, soil core samples were fully saturated keeping in a tray filled with water in such a way that the water can be sucked through top soil as happens in field situation. Then, the measurement were taken keeping time interval of 30 minutes for each reading. The repeated readings were recorded until constant value was observed for each sample. Based on flow of water from the soil column time interval was either reduced - samples with high flow or increased - samples which have low flow. The following equation was used to calculate Ksat:

$$\boldsymbol{Ksat} = (\boldsymbol{V} * \boldsymbol{L})/(\mathbf{A} * \mathbf{h} * \mathbf{t})$$

Where, V= volume of water flowing through the sample (cm^3), L= length of soil column (cm),
h = water level difference inside and outside sample core (cm), A= Surface area of core sample (cm^2),
t = time interval between beginning and end of the measuring (min).

Porosity measurement

Porosity was measured by applying 'saturated moisture content' method, simply assuming there is no entrapped air inside soil pores when soil column completely saturated. Fully saturated 22 soil core samples immediately after weighing were kept inside the oven at 105^0c. First measurement of dry weight of samples made just after 24 hours and repeated until the constant weight recorded. Following equations were used to calculate porosity:

$$\mathbf{Wwtr} = \boldsymbol{Wsat} - \boldsymbol{Wdry}; \quad \boldsymbol{Vp} = \boldsymbol{Wwtr}/(\rho\, \mathbf{Wtr}); \quad \boldsymbol{Porosity} = \boldsymbol{Vp}/\mathbf{Vt}$$

Where,

Wsat = Saturated weight of soil core, Wdry= Dry weight of soil core, Wwtr = weight of water, ϱ wtr = density of water, Vp= pore volume of soil, Vt = total volume of soil

Bulk density (BD) measurement

The 'Dry soil weight' was the method applied for BD estimation. All saturated soil samples were dried at 105^0c at least for twenty four hours and continued until the constant weight obtained. Fourteen samples were found with considerable amount of gravels. Thus, following methods described in Throop et al., 2012, mass and volume correction of gravels (>2 mm) was performed. Following formula was used to calculate bulk density: $\boldsymbol{BD} = \boldsymbol{Wsdry}/\mathbf{Vstot}$

For gravel correction, $\mathbf{Wcor} = \boldsymbol{Wsdry} - \boldsymbol{Wgr}$; $\mathbf{Vcor} = \boldsymbol{Vstot} - \boldsymbol{Vgr}$; $\boldsymbol{BDcor} = \boldsymbol{Wcor}/\mathbf{Vcor}$

Where,

Wsdry = dry weight of soil core, Vstot = total volume of soil core, Wgr = weight of gravels, Vgr = volume of gravels, Wcor = corrected weight of soil, Vcor = corrected volume of soil

Soil organic matter (SOM) estimation

Soil organic matter was estimated by 'loss of ignition' (LoI) method, which is a complete burning of available SOM. For this, all soil samples (about one gram) were kept into muffle furnace at 520^0c. The SOM was calculated as: $\boldsymbol{SOM}\,(\%) = (\mathbf{Wsint} - \mathbf{Wsig})/\mathbf{Wsint} * \mathbf{100}$;

$$\boldsymbol{SOM}\,(\%)\,\mathbf{of\ total\ soil} = (\mathbf{100} - \%\,\boldsymbol{fraction} > \mathbf{2}\boldsymbol{mm})/\mathbf{100} * \boldsymbol{SOM}(\%)$$

Where,

Wsint = initial weight of soil, Wsig = ignited weight of soil

Soil texture analysis

The particle size analysis was done adapting 'pipette method' proposed in (van Reeuwijk, 2002). Firstly, soil samples made homogenized without disturbing natural texture. Then the course fragments (>2mm) were separated, washed with demineralized water, dried them at 40^oc and weighed. After that approximately twenty gram of fine soil (< 2mm) of each sample was taken, SOM was oxidized by adding H_2O_2, 30% and followed end-over end shaking to disperse particles. The separation of fractions begun with wet sieving of suspension through 50 micron sieve. Twenty millilitre suspension of each sample at immediately after 1 minute, 5 minutes and 5 and half hours settling of particles from the defined height (based on temperature of blank solution) of the suspension after sieving (1000 ml) was taken and dried at 105^0c overnight. The dry and cooled fractions of samples were weighed. Sand fraction was further sieved (1, 0.50, 0.25, 0.1 and 0.05 mm sieve series) to find the separate sand fraction percentage. Finally, sand, silt and clay percentage were calculated as follows:

$\text{Clay}\ (< 2\ \mu\text{m}) = (\mathbf{H} \times 50) - (\mathbf{Z} \times 50)\,(\text{wt.}\,\mathbf{K})$; $\text{Silt}\ (2 - 20\ \mu\text{m}) = (\mathbf{G} \times 50) - (\mathbf{Z} \times 50) - \text{K}\,(\text{wt.}\,\mathbf{L})$

$\text{Silt}\ ((20 - 50\ \mu\text{m}) = (\mathbf{F} \times 50) - (\mathbf{Z} \times 50) - \text{K} - \text{L}\,(\text{wt.}\,\mathbf{M})$; $\text{Sand}\ (> 50\ \mu\text{m}) = \mathbf{A} + \mathbf{B} + \mathbf{C} + \mathbf{D} + \mathbf{E}\,(\text{wt.}\,\mathbf{N})$;

$\mathbf{Sample\ weight} = \mathbf{K} + \mathbf{L} + \mathbf{M} + \mathbf{N}$ (All weights in gram);

$$\%\,\mathbf{fraction}\ (\mathbf{clay}, \mathbf{silt}, \mathbf{sand}) = (\mathbf{fraction\ weight}\ (\mathbf{K}, \mathbf{L}, \mathbf{M}, \mathbf{N})/\mathbf{sample\ weight}) * \mathbf{100};$$

$$\%\,\mathbf{fraction}\ (\mathbf{clay}, \mathbf{silt}, \mathbf{sand})\,\mathbf{of\ total\ soil} = (\mathbf{100} - \%(\mathbf{fraction} > \mathbf{2mm} + \mathbf{SOM})/\mathbf{100}) * \%\,\mathbf{fraction}\ (\mathbf{clay}, \mathbf{silt}, \mathbf{sand})$$

Where,

A through E = weight individual sand fractions; **F**= weight 20 ml pipette aliquot of fraction <50 µm; **G**= weight 20 ml pipette aliquot of fraction <20 µm; **H** = weight 20 ml pipette aliquot of fraction <2 µm; **Z** = weight 20 ml pipette aliquot of blank

For the quality control, one reference sample from Nepal, two duplicate samples (sample 6 and 20) and one blank were also considered for whole procedure.

3.5.2. Estimation of fine sediment fraction of landslides and debris flows

Dry sieve analysis was performed after preparation of all samples by air drying. The sieve set included sieves of 2, 1, 0.50, 0.25, and 0.125 mm. The total sediments that has taken and the sieved sediments that has retained in each sieve and also in pan were weighed and percentages for each categories was calculated.

3.6. Input data preparation for RMMF erosion model

Processing of not only secondary data acquired from various sources but also field and laboratory data essential to be prepared as inputs for the erosion model are also described in this section. The data were grouped in four separate categories: 'topographical', 'meteorological', 'land use and vegetation', and 'soil' for 2014, and landslides 'runout extent' as an additional for 2015. Then all data were processed as per necessity of RMMF model using ERDAS IMAGINE 2015, ArcGIS 10.3, Microsoft excel and finally PCRaster software.

3.6.1. Topographical data: DEM and its derivatives

Digital contour lines of topographic map – 1: 25,000 (three sheets) were merged together, checked if the connection of each contour was properly matched in merged layer. As shown in Appendix 6-b, using 'Terrain 3D surfacing' contour lines were interpolated by non-linear rubber sheet in ERDAS EMAGINE. Thus prepared DEM of 10 m resolution, furthermore had undergone 'hydrology – fill' operation to modify the elevation values so that trapping of water in the pixels that are surrounded by pixels of higher elevation could be eliminated. Slope gradient (Figure 2-2), and local drain direction (Figure 4-1) were prepared in PCRaster from DEM using spatial calculator 'pcrcalc'.

3.6.2. Meteorological data: rainfall and evapotranspiration (ET)

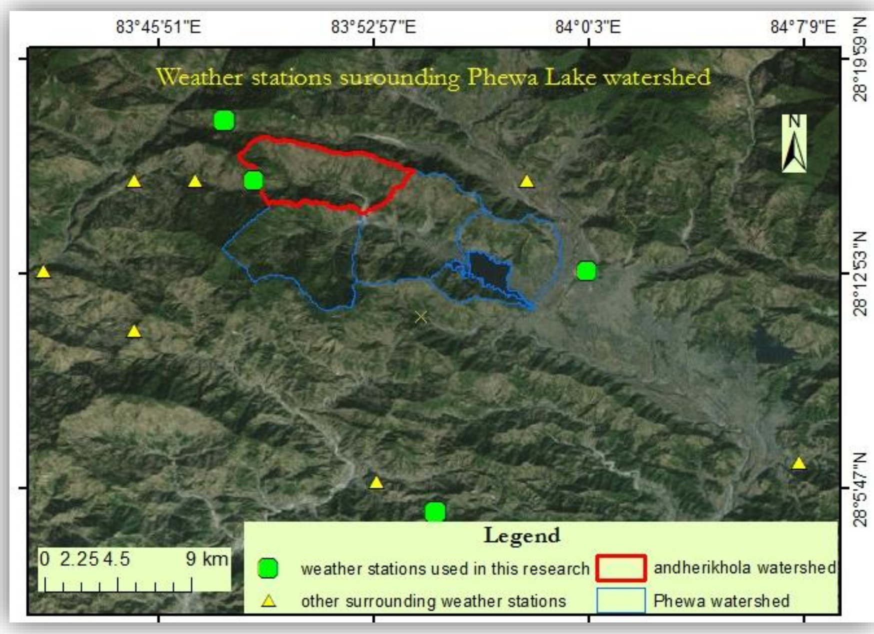


Figure 3-3: Meteorological stations surrounding the Phewa Basin including four (rainfall-2 plus temperature-2) stations used in this research.

Rainfall data of 14 different surrounding stations (Illustrated in Figure 3-3) of 30 years (1984/85 - 2014/2015) were collected and checked the consistency and the gaps. Local precipitation pattern was analyzed using few interpolation techniques, for example 'inverse distance', 'ordinary krigging', and also 'regression analysis' with elevation (Figure 4-2) before taking decision which and how many stations to be selected for this study (see **Section 4.2**).

Temperature data of 2014 (pre-landslide situation) and 2015 (the year of massive landslide incidences) were used for the calculation of 'reference evapotranspiration' (ETo). Unlike rainfall data temperature data are hard to access because many of meteorological stations nearby record only precipitation data. Thus based on data availability 'Lumle' (83.8 E, 28.3 N, elevation1740 msl) and 'Dandaswarna' (83.9 E, 28.08 N, elevation 1432 msl) stations were considered for 2014, and 'Lumle' and 'Pokhara Airport' for 2015 (remarkable gaps in the data of 'Pokhara Airport' for the year 2014). The ETo, 'Blaney-Cridle method' (Doorenbos and Pruitt, 1977), was calculated by the formula as:

$$\mathbf{ETo} = \mathbf{c}[\mathbf{p}\ (\mathbf{0.46T} + \mathbf{8})]$$

Where,

ETo = reference evaporation in mm/day; T = Mean daily temperature in ^{0}C over the month considered;

P = mean daily percentage of total annual daytime hours for a given month and latitude;

c = adjustment factor based on local minimum relative humidity, sunshine hours & wind speed.

3.6.3. Land use and vegetation data

Land cover/use map

A combined qualitative and quantitative integration approach was adapted to prepare a land cover/use map which includes 'dense forest', 'open forest', 'paddy field', 'rainfed cultivation', 'pasture', 'abandoned cultivation', 'settlement', 'bare surface', 'river sand/flood plain', 'river water', and 'pond' for 2014, and an additional class 'landslide' in case of 2015. As shown in flow chart in Appendix 6-c), firstly, supervised classification (maximum likelihood) of image 2013, and 2015 has done making training data sets (Forest: 27, Cultivation: 34, River: 47 and Pasture: 11) in ArcGIS 10.3 (see map in Appendix 6-d), aiming to delineate forest, cultivation and river. While cleaning, delineation of river was noticed not well by this method. Therefore all pixels were deleted making sure the remaining pixels were strictly related to forest and cultivation. The intact forest and cultivation area for long time were also compared with baseline land cover map of 1992. The land cover/use individual layers i.e. pasture, river, abandoned cultivation, open forest, pond for 2014 and also landslides and river in case of 2015 were produced by visual interpretation and digitization. Settlement layer obtained from UNIL was edited for the year 2014 and used same layer 2015 assuming no significant change within a year in rural catchment which was also not noticed during field visit. Thus prepared individual land cover layers overlaid (union) separately for 2014 and 2015. Finally, cleaning (eliminate sliver polygons, erase duplicate polygons, and update overlapped ones) has performed to get land cover/use map. The role of paddy field in downslope and rain fed cultivation in upslope is different. Therefore, partition of paddy fields and rain fed cultivation was made making assumption based on local practices i.e. the paddy fields usually lie (1) in lower elevation, (2) in the areas where water is available to irrigate, and are (3) not very close to the settlement. Delineation of paddy field by this method, however was not depicting the field practices. Hence, paddy layer was also prepared by visual interpretation and digitization and verified with GPS locations, and photographs collected from the fields and knowledge obtained during field visit about land use practices. Finally, overlay function was used (intersect, erase and union) to get final land cover map with 12 classes (2014), and 13 classes (2015) (see individual flow chart for 2014 and 2015 in Appendix 6-e & 6-f).

Normalized difference vegetation index (NDVI) map series

The eMODIS NDVI (Terra) regional (Asia) map series of 250 m resolution data were firstly downloaded (prepared averaging 10 days data and published in each fifth day). Next, NDVI maps were processed and resampled ('cubic') in ArcGIS 10.3 using 'spatial analysist' tools to get 10 m resolution NDVI map series (flow chart in Appendix 6-g), and further interpolated to get daily NDVI maps of 2014 and 2015 separately in PCRaster. Resampling from 250 to 10 m resolution has obviously some effects but preparation of such data using high resolution images is very costly (freely available are coarser than eMODIS NDVI e.g., SPOT NDVI- 1 km) and MODIS has high temporal scale which provides the chance of capturing the day to day vegetation changes in the locality.

Vegetation parameters

Plant height (PH), interception (A), canopy cover (CC), surface cover (SC), ratio of actual (Et) and potential (Eo) evapotranspiration (Et/Eo) are inputs for RMMF that come from land cover, NDVI daily map series, field observation, and literature (i.e. PH, effective hydrological height-EHD), and some (i.e. Kc) came from guide values (Morgan, 2005). All required parameter values were organized in a land use table.

3.6.4. Soil data

Soil unit map

'Land systems map' obtained from GoN (1985b) was scanned, georeferenced and digitized. All attribute information were updated by adding field and attribute editing which included 'dominant soil types', 'dominant texture', 'soil drainage' and 'landforms'. Similarly, the vector layer of geology with some geomorphological information acquired from GoN- DMG, with no data in western part of the watershed, was edited. The information in no data area were updated using 'geological map' (GoN, 1985a) and overlaid (union) with soil map so that information about parent materials would also be included in the map. This map has very general information of soil parameters (see map in Figure 4-4 & flow chart in Appendix 6-h). Therefore the units of land cover/use map has also taken as the soil unit map as a best approximation, and because the soil data have also been collected on different land covers/uses in the field.

Soil Parameters

Soil parameters values obtained from laboratory analysis (Section 3.5.1) were grouped as per land cover/uses type. The minimum, maximum and average values of all parameters (Cohesion, Ksat, Porosity, BD, SOM, > 2 mm fraction, Sand, Silt, and Clay) were calculated; 'field capacity' and 'wilting point' have derived from 'soil water characteristics' software using aforementioned texture information (Saxton and Rawls, 2009) and finally, put them in a table (see min, max, and mean values per land use units in Table 4-2) so that it can be used in PCRaster for erosion modelling later.

3.6.5. Data about runout extent of landslides and debris flows

Areal extent of runout of all debris flows and landslides that happened in 2015 were visually interpreted and digitized using RapidEye satellite image – 4.8 m resolution (2015). And supporting field information (particularly when the runout on densely forested steep slopes is not visible in satellite image). Later, the digitised layer was crosschecked with – 2m resolution image of 2016 (also available in google earth now).

3.6.6. Material volume of landslides and debris flows

Firstly, debris flow runway was categorised into three different zones viz. 'release', 'transport' and 'deposit'. The deposit zone is further defined as 'intermediate/upslope deposit' and 'end deposit'. Afterwards the 'area-height' or 'area-length' approach was adapted to estimate volume of materials for each zone. Four different mathematical models: (1) planar area (ArcGIS polygon area), (2) triangular prism, (3) parabolic section (4) rectangular prism, were applied for the delimitation of area. Following formulae were used to calculate volume of the materials (Simmons, 2016; MathWarehouse, n.d.):

1. Volume = area of runout section × height
2. Volume = area of triangle × length of section
   $$= \left(\frac{1}{2}\mathbf{b}\ x\ h\right) x\ L$$
3. Volume = area of parabola × length of section
   $$= \left(\frac{2}{3}\mathbf{w}\ x\ h\right) x\ L$$
4. Volume = width × length × height

Area of runout section for 1 has calculated taking 'planar area' i.e. digitized from satellite image In second case, debris flow channel is assumed to be 'V-shaped'; surface area thus calculated for a triangle and multiplied by length of particular runout section to get volume. In third model, the shape of debris flow channel was supposed as a parabola and area as well as volume were calculated accordingly. In 'rectangular prism' volume is calculated by multiplying average width, average length and average height of the runout segment considered.

3.7. RMMF erosion model simulation

3.7.1. Reasoning why RMMF selected

The RMMF erosion model has been selected for this research. Unlike physics-based models it can still be used in case of limited accessibility and quality of baseline data (Jetten et al., 2003). It is also applicable in wider range of geographical areas including tropical Himalaya (Morgan, 2011). Furthermore the RMMF model has been recently implemented for daily basis erosion estimation in PCRaster modelling environment (Shrestha and Jetten, 2016).

3.7.2. Model overview

RMMF is an annual distributed grey box or conceptual model applied at plots, hillslopes and small catchments. The basis is on physical processes that govern a system, unlike physics based model it describes the processes by empirical relationships for soil erosion prediction. **RMMF** describes erosion as 'water phase' and 'sediment phase', water phase describes the rainfall energy to detach soil particles and volume of runoff from hillslope while the later explains rate of detachment by rainfall and runoff and also transportation by runoff (Morgan, 2005, 2001). Moreover, MMF 2008 version (Morgan and Duzant, 2008) emphasizes the role of vegetation cover on erosion prediction counting plants stem and stem diameters; the processes are simulated separately for sand, silt and clay considering the different response of particle sizes; and deposition is modelled recognizing particle settling velocity, flow velocity, flow depth and slope length.

3.7.3. Adaptation to daily time step

Bearing in mind, continuous sediment distribution path and deposition spots that would be delineated onto the hillslope and the river valley, RMMF has adapted to daily time step by Shrestha and Jetten (2016), where daily input data viz. rainfall, evapotranspiration, and cover (derived from NDVI maps) are used (see flow diagram in Figure 3-4). For better estimation of interception 'leaf area index' (LAI) and maximum water storage on leaves are also incorporated. Other parameters such as EHD, PH, cohesion, saturated hydraulic conductivity, porosity, BD, soil detachability index, field capacity and wilting point are used based on land use and soil unit map. The script explaining equations that has applied in RMMF, and other formulations are written in PcRaster platform.

3.7.4. Sensitivity analysis

Sensitivity of daily maximum and annual totals of model outputs were analysed by simply following "one at a time" method varying the value of single input parameter or a combined of very closely related parameters for example porosity and Ksat at a time keeping others constant. The variation has made by two ways:

(1) Changing ±10 % and ± 20 % from 'base'. The base was 'mean value' for soil parameters and initially decided base value for vegetation parameters. The limit of variation (base±10 % and base± 20) was decided so that changed values lie well above minimum and well below maximum observed/measured values.

(2) Considering measured low, and high values of soil parameters (Morgan and Duzant, 2008). Afterwards, relative sensitivity (RS) and average linear sensitivity (ALS) were calculated as follows:

$$\text{RS}= \frac{O_1-O_2}{O} / \frac{I_1-I_2}{I} \qquad \text{ALS}= \frac{O_1-O_2}{mean} / \frac{I_1-I_2}{mean}$$

Where,

O_1 & O_2 = values of model outputs, I_1 & I_2 = values of input parameters;

I= base value of input parameters; O = output with I; mean = average of two outputs and two inputs

The former assessment (base ±10 %; base ± 20 %) has made before the adjustment to the model for Himalayan watershed and the later has done after the application of all adaptation measures.

3.7.5. Adaptation for Himalayan catchment

Adaptation has made giving consideration to the initial simulation outputs (explanation is in section 5.1) which were very far from the real situation in the catchment. As illustrated in figure 5.2, decisions have made in a series of steps which begun with the changes on guide values, e.g. EHD, SC. The basis are the local literature (eg. GoN, 1985b) and judgement considering unique characteristics of the locality (e.g. vegetation/forest types, local cultivars). Evaluating the performance of model with 'minimum', 'mean' and 'maximum' values of soil parameters (Table 4-2), which set of value to be taken for further steps was determined. Next, the model enactment was analysed by 'sensitivity analyses' of model outputs to major input parameters. Doing so, fundamental adaptation measures that need to take on RMMF daily erosion model were identified which can enhance the reliability of the soil loss predictions in Himalayan catchments.

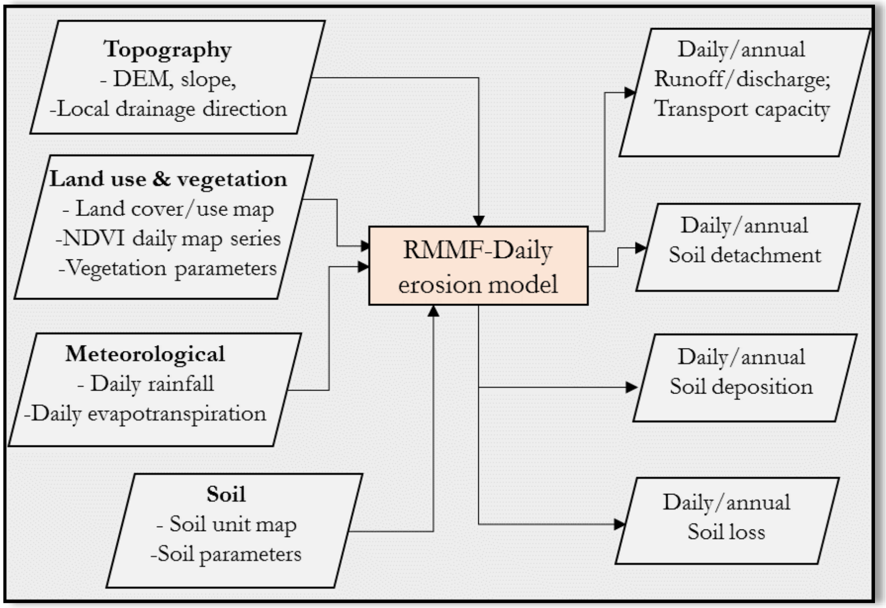


Figure 3-4: Soil erosion modelling by RMMF daily erosion model.

3.7.6. Simulation

Simulation has done making two different considerations: (1) 'initial simulations' that has run with no adjustment on RMMF-daily model; (2) later one is with adaptations for the applicability to Himalayan basins' particularly of lesser Himalaya.

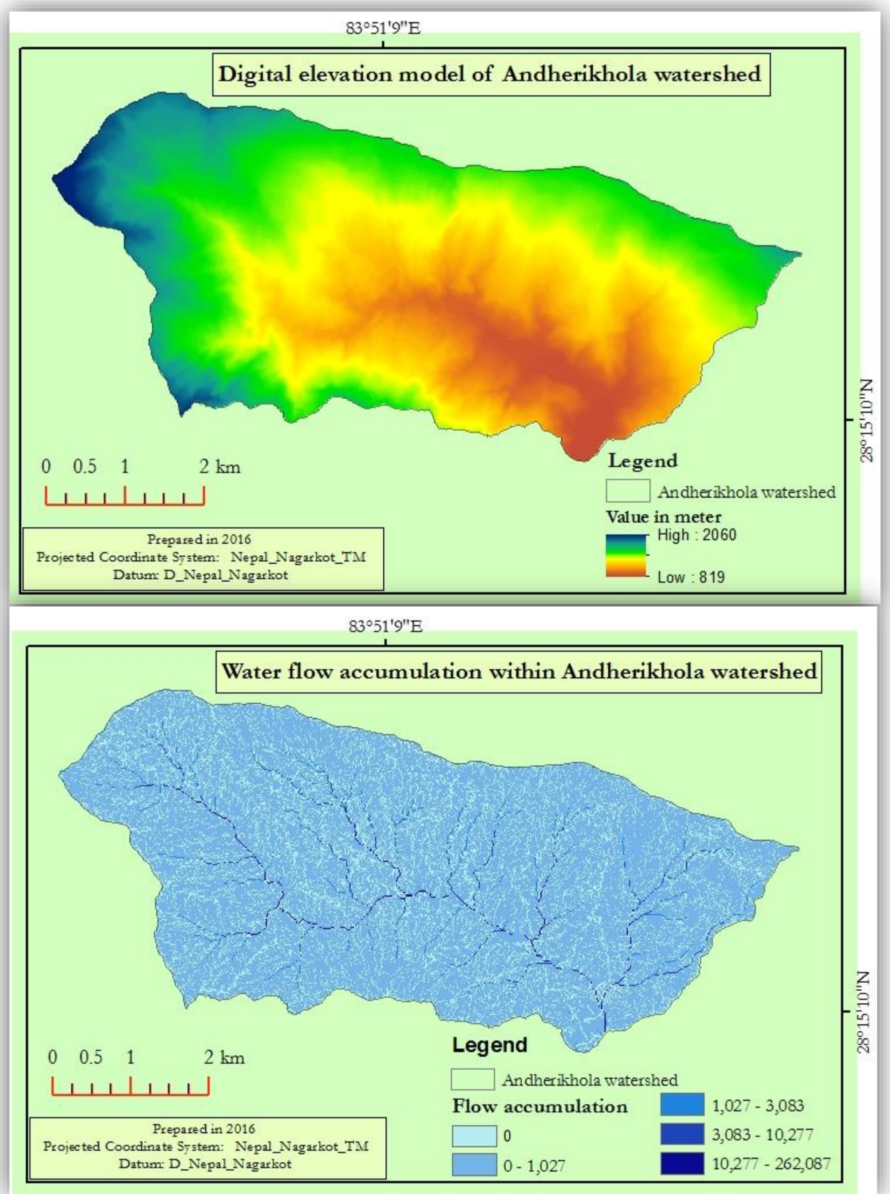
Simulation without adaptation: Firstly, initial simulations were carried out with 'mean', 'minimum' and 'maximum' soil parameters separately keeping vegetation parameters constant. Later, the model was repeatedly run changing the value of each soil parameter in each replication. Doing so, attention has paid to change values of closely related parameters such as while replacing value of porosity, Ksat has also been changed. Next, vegetation parameters – surface cover and plant height – were changed. Since, MMF is basically hillslope model, in-stream erosion in higher order streams has been suggested to be ignored (Shrestha and Jetten, 2016). However, simulations with or without including erosion in >3rd order streams have also executed.

Simulation for Himalayan environment: As described in section 3.7.5, fitting of the model for catchments in Himalayan settings particularly in middle mountains where the study area is located was done in series of steps. When results have obtained near to the reality of the basin, modifications were stopped. However, multiple simulations were run with revised value of individual parameter to assess the implication on final product.

4. BASELINE DATA FOR RMMF MODEL

As explained in section 3.6, the input data are of four different categories: **topographical** – DEM and its derivatives; **meteorological** –rainfall and evapotranspiration; **land use and vegetation** – land cover/use map, crown cover, surface cover, and plant height; and **soil** –soil unit map, field capacity, wilting point, cohesion, porosity, saturated hydraulic conductivity, bulk density, soil texture (percentage of coarse fraction, sand, silt, clay), effective hydrological height, and soil organic matter. This chapter describes the results of such data achieved by ancillary data processing, field observation, and laboratory analysis.

4.1. DEM and DEM derivatives



The DEM is of 10 m resolution with elevation range of 819 to 2064 msl (Figure 4-1). The slope varies between 1 and 75 degrees which was presented in five classes (see Figure 2-2) with dominancy of 11-19 and 20-30 degrees in terms of area i.e. 8.35 and 10.35 km² respectively. Local drainage direction (LDD) (Figure 4-1, bottom) shows combination of semi dendritic and semi parallel drainage pattern. The DEM was made from contour of 1992; but flood plains are very dynamic and PCRaster and ArcGIS approach for LDD are also different. Therefore, the hillslope area in north eastern edge and mouth of the river are slightly differ (see difference between Figure 4-1 & Figure 5-7).

Figure 4-1: Digital elevation model (top) and flow accumulation (bottom) of Andherikhola basin.

4.2. Rainfall and Evapotranspiration

Rainfall seems increasing with elevation when observed data lie within or close to the valley (Ramsay, 1985). However, if observed data mixed with two or more nearby valleys the dependency of rainfall with elevation goes poor. For instance, in Figure 4-2, the left plot has regression coefficient of 0.5963 in consideration of 5 stations, whereas R^2 was decreased when other distant stations were included.

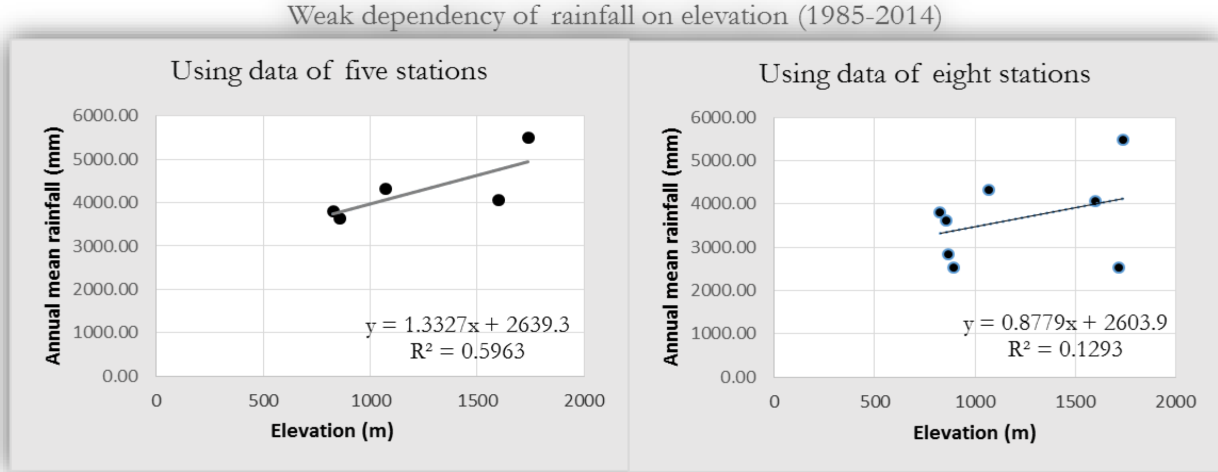


Figure 4-2: Scatter plot of annual mean rainfall versus elevation.

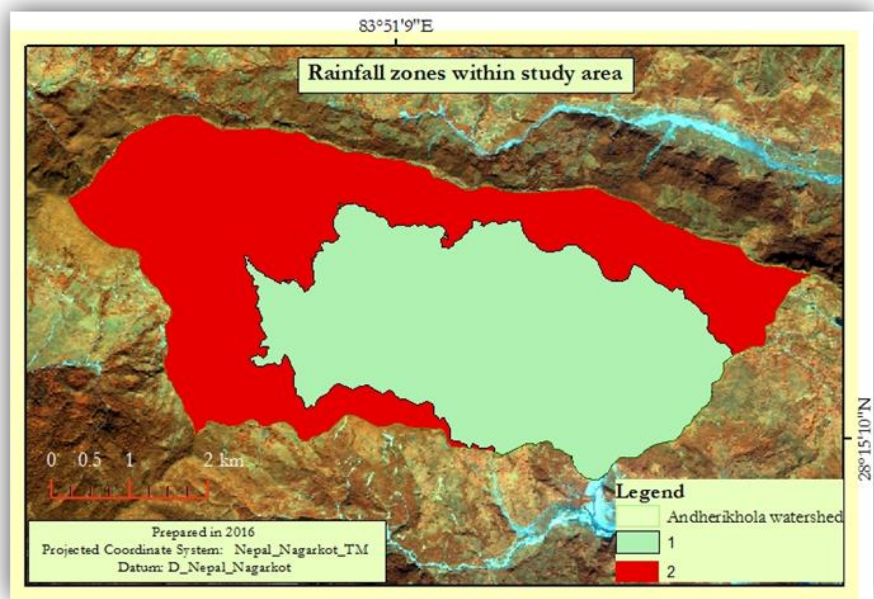


Figure 4-3: Rainfall and ET zones considered for this research.

The macro/microclimate and weather pattern is very site specific, and remarkable variation amongst nearby valleys were observed in the study area. Therefore, two nearest station, 'Pokhara Airport' (84.000 E 28.21666667N, elevation 827 msl) outside the phewa watershed and Bhadaure deaurali (83.81666667E, 28.26666667N, elevation 1600 msl), outside but very close to the Andherikhola watershed were selected for rainfall data.

But as mentioned in section 3.6.2, other two stations (Lumle and Dandaswarna) has chosen for temperature data. Based on the location of meteo-stations, 'on-site observation' of various forest ecosystems and existing agricultural practices, past literature, and opinion of people, two zones were delineated for the use of meteorological data. Zone 1≤1299 m comprises 13.011 km² and zone 2 ≥1300 m includes 13.59 km² area out of total area of basin - 26.60 km² (Figure 4-3).

The calculated daily evapotranspiration values are ranged between 2.65 and 6.26 with average of 4.51 for 2014, and 2.99 to 6.73 with average of 5.03 mm for 2015 for zone 1. Similarly it ranges from 2.52 to 5.80 with mean value of 4.32 mm for 2014 and 2.62 to 5.87 with mean of 4.32 mm for 2015 for zone 2.

4.3. Land use and vegetation

Land cover/use, and NDVI map series are very important input maps for the RMMF model. Separate sets of maps were prepared for baseline erosion modelling (2014), and for post-landslides situation (2015). As shown in Figure 4-4 land cover/use classes for first are 12 and 13 for later including landslides area as a new class (see separate landslide map of 2015 in Figure 6-1).

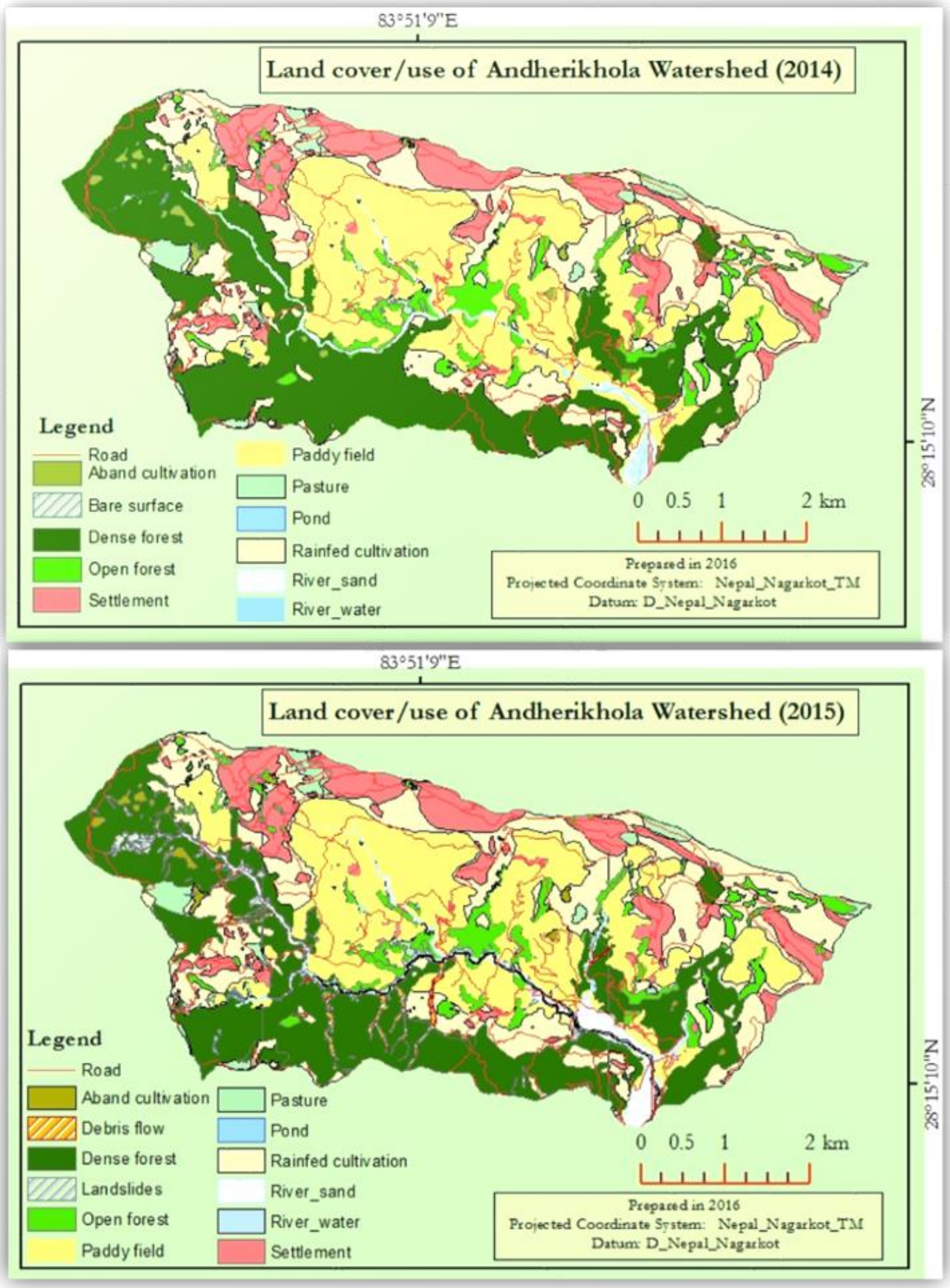


Figure 4-4: Land cover/use of Andherikhola watershed, with 12 classes for base year, 2014 (top), and 13 classes including recent landslides and debris flows for the year 2015 (bottom).

However, in view of the area and feature types of each land cover/use class, some classes for instance, pond and road, (plus bare surface for 2014) were ignored during simulation.
Separate delineation of paddy fields, and rainfed cultivation has performed paying attention to the contrast responses to erosional processes (see for example, Shrestha et al., 2004), however some overlapping has still unavoidable. It depends on choice of people (preference is always paddy cropping unless soil quality and water availability do not favour) and in some occasions the local policies (see Tamura, 1996). Moreover, naming forest either 'dense' or 'open' is solely in due consideration of possible effect on hydrologic response (e.g. interception, and runoff generation) by isolated small patches and mature forest in intact larger areas.
Compare to 2014, forest, paddy and rainfed cultivation areas have reduced by 55, 29, and 6 hectors in 2015, whereas river flood plain has widened covering 31 ha of new area because of the landslides incidences (areal values for all land cover/use units considered are in Appendix 7). Landslides runout area including debris flows is of 52 ha which is remarkably high in comparison with 2014, where 3 ha area lies under this category (named as bare surface).
Most of the vegetation parameters such as 'cover', 'leaf area index' for 'interception', Et and SC factors were derived from NDVI and land cover/use maps by applying 'empirical equations'. Total of 53 NDVI maps for 2014 and 69 for 2015 were selected eliminating the ones with substantial cloud coverings (see an example daily map in Figure 4-5, and NDVI values for selected maps in Appendix 8). Moreover, PH, EHD, surface cover (SC) factor, and crop (Kc) factor were used as presented in Table 4.1.

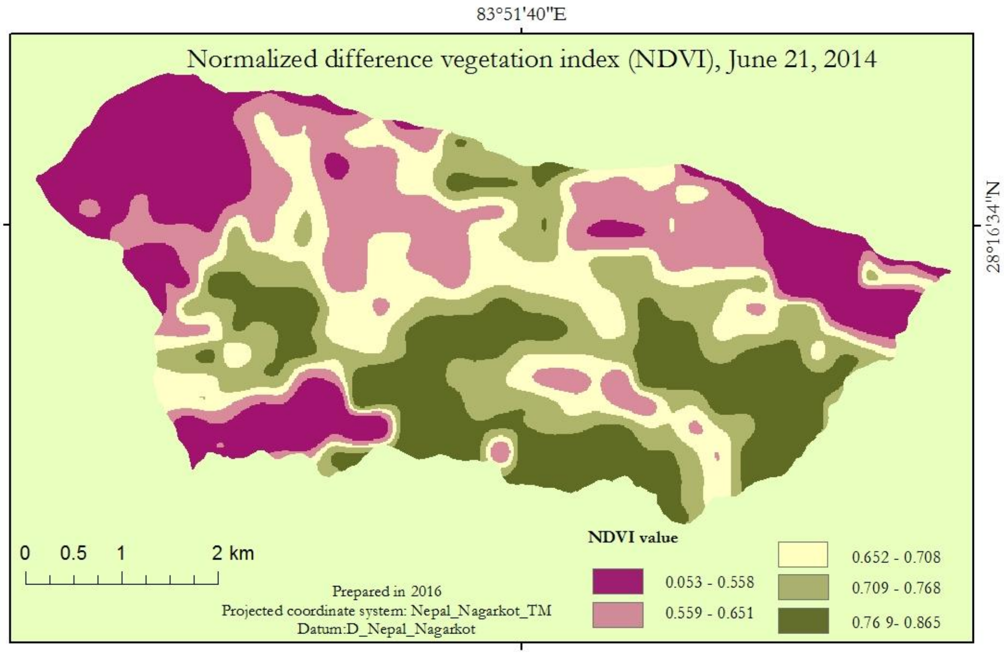


Figure 4-5: An example of daily NDVI map of 172 day of the year 2014 (June 21, 2014).

Table 4-1: Plant parameters as direct input to RMMF model.

Land cover/use	PH	SC factor to cover	EHD*	Kc
Dense forest	5	0.80	0.35	0.20
Open forest	4	0.70	0.30	0.20
Paddy field	0.7	0.50	0.30	0.15
Rain fed cultivation	1.2	0.60	0.25	0.15
Pasture	0.8	0.70	0.30	0.14
Abandoned cultivation	1.2	0.70	0.35	0.12
River flood plain	0	0	0.20	0.09
Landslides	0	0	0.25	0.05

*EHD has revised based on soil map (Figure 4-6) which provides soil drainage information.

4.4. Soil unit map and parameters

Baseline soil map provides very general information about soil types, texture and parent materials with overlapping information between units. The whole area comprises mainly of two units (Figure 4-6). But the information about soil drainage i.e. soil with 'moderately well to well drainage capacity' and the 'seasonal depth of surface to water table' has provided the basis to adopt EHD values during simulation.

Most of soil parameters showed remarkable heterogeneity (Appendix 9 and 10, and Table 4-2 elucidate all values of soil parameters considered). For instance, Ksat values were estimated as 0.0001 to 1044.71 with mean value of 190.17, standard deviation from mean 304.11 mm/hr and coefficient of variance 159.90 %. Likewise, cohesion, porosity, BD, and SOM have shown large variation. Fourteen different samples were observed with course fragments, ranged from 2.37 to 57.70 percent by weight with average of 8.52.

The total sand estimated lies between 9.12 and 56.99 with mean of 28.91, standard deviation 13.55 %. The silt values lied between 18.05 and 54.98 with mean value of 37.32, SD of 9.95 and CV is 26.67%. Likewise, the lowest clay percent was 1.74 and the highest was 33.19 with average-15.29, SD-9.38, and CV-61.31%. Textural classes of the soil samples were obtained as 'loam', silty loam', 'sandy loam', and 'silty clay loam'.

22 samples in a 27 km² watershed with a remarkable heterogeneity may not good representation of real field situation. To address this uncertainty, results were grouped per land use classes. Table 4-2 includes minimum, maximum and mean values of soil parameters for each land cover/use unit. Soil parameters in land use wise grouping also has variation within a group. However, this gives at least separate spatial unit with average soil condition. For example, dense forest (DF) has high Ksat, porosity, and SOM with mean value of 305.35 mm/hr, 67.48%, 14.60 % respectively; moderate cohesion (124.55 kPa), and low BD (0.77 g/cm³). On the contrary, open forest (OF) has high BD (1.30 g/cm³), Ksat (321.69 mm/hr) and low cohesion (110.33 kPa), and SOM (4.33%), and the lowest of porosity (36.95%).

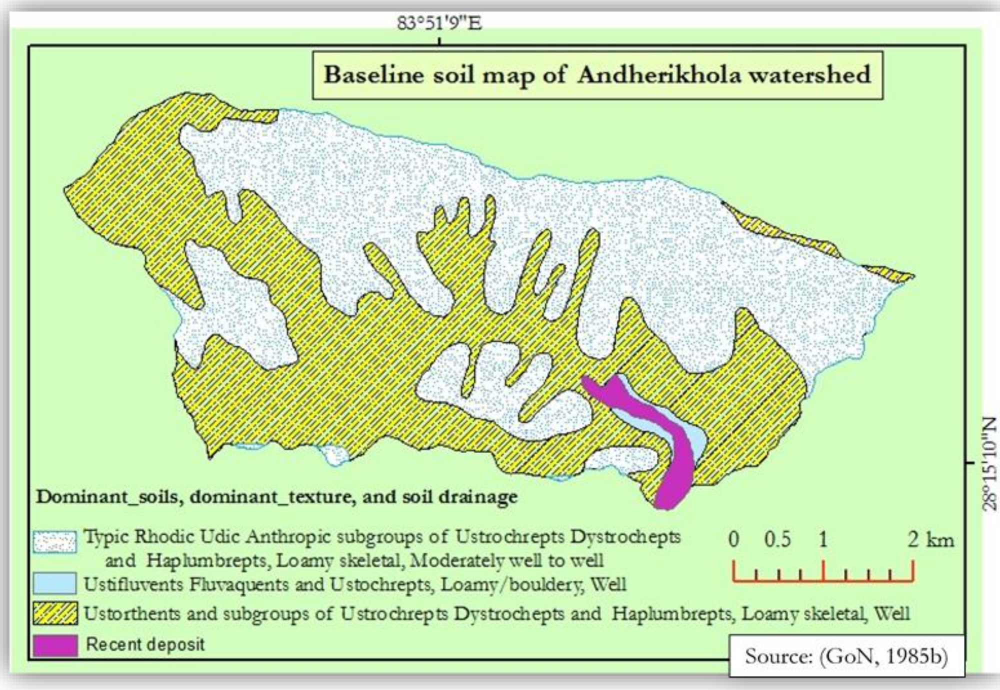


Figure 4-6: Baseline soil map prepared from 'Land systems map' 1985.

High porosity, Ksat and SOM, and low BD have observed in this research compare to the 'past studies in middle mountains' (Nepal). This is so because most of the studies had given consideration to the top10 cm to 50 cm depth of soil layer (e.g. Ghimire et al., 2014; Begum et al., 2010). But, bearing in the mind the importance of the top soil of few centimetres especially in erosion processes (e.g. providing surface cover, holding water and gradual supply for infiltration, preventing evapotranspiration during dry period), this study has considered the top 5cm of soil profile. In addition, in some cases sampling error has noticed for instance, high Ksat in sample 2 and 7 were because of macrospores. And it is unavoidable since the continuation of root breaks if you sample soil by 'core sampling' method.

Table 4-2: Soil parameters values per land cover/use classes.

		Dense forest	**Open forest**	**Paddy field**	**Rainfed cultivation (Bari)**	**Pasture**	**Abandoned Cultivation**
		n= 5 (6*)	n= 4	n= 4 (7*)	n=5 (7*)	n=2 (4*)	n=2
	Min	64.73	58.84	82.38	58.84	68.26	147.10
	Max	170.64	223.60	235.36	176.52	189.47	194.17
Cohesion*	**mean**	**124.55**	**110.33**	**165.59**	**96.33**	**120.33**	**185.35**
Kpa	**SD**	43.94	76.17	64.85	38.89	50.68	12.48
	Min	12.03	15.21	0.00	0.28	0.74	1.86
	Max	682.92	1044.71	568.06	11.82	61.40	685.59
Kast	**mean**	**305.35**	**321.69**	**145.58**	**7.69**	**31.07**	**343.72**
mm/hr	SD	296.30	486.30	281.68	6.23	42.89	483.47
	Min	56.00	21.00	54.38	49.14	47.13	53.02
	Max	72.87	58.70	64.00	59.66	67.00	63.00
	mean	**67.43**	**36.95**	**61.51**	**55.32**	**57.06**	**58.01**
Porosity	**SD**	7.04	18.19	4.99	4.31	14.05	7.06
(% vol.)	Min	0.61	1.03	0.98	0.97	0.89	0.96
	Max	1.23	1.46	1.12	1.22	1.33	1.12
	mean	**0.77**	**1.30**	**1.06**	**1.13**	**1.14**	**1.06**
BD g/cm3	**SD**	0.28	0.25	0.08	0.10	0.30	0.13
	Min	8.13	2.07	6.06	7.37	4.81	7.18
	Max	18.78	7.82	11.53	12.49	16.60	14.62
SOM (%	**mean**	**14.60**	**4.33**	**9.13**	**9.68**	**10.71**	**11.21**
wt.)	**SD**	4.38	2.64	2.68	2.20	8.34	4.82
	Min	0.00	7.89	0.00	0.00	0.00	0.00
	Max	6.68	57.70	5.44	13.49	6.78	12.29
>2mm (%	**mean**	**2.60**	**28.99**	**1.95**	**6.33**	**3.39**	**6.14**
wt)	**SD**	3.56	24.07	2.58	6.00	4.79	8.69
	Min	13.99	19.87	9.12	11.49	42.77	13.13
	Max	56.99	45.55	30.42	51.20	43.37	24.61
Sand	**mean**	**32.04**	**35.34**	**20.97**	**25.34**	**43.07**	**18.87**
(%wt)	**SD**	15.79	10.94	9.08	16.24	0.42	8.12
	Min	26.66	18.05	47.51	27.43	25.70	37.21
	Max	42.58	37.89	54.98	46.46	37.54	40.19
	mean	**34.47**	**27.54**	**49.89**	**39.66**	**31.62**	**38.70**
Silt (%wt)	**SD**	7.08	10.92	3.48	8.06	8.38	2.11
	Min	5.16	1.74	8.54	10.18	8.09	18.09
	Max	26.45	5.61	29.18	33.19	14.34	32.06
	mean	**16.29**	**3.81**	**18.06**	**18.99**	**11.21**	**25.07**
Clay (%wt)	**SD**	7.67	1.89	8.78	9.94	4.42	9.88
	Min	39.20	14.70	38.06	34.40	32.99	37.11
Field	Max	51.01	41.09	46.20	41.76	46.90	44.10
Capacity	**mean**	**47.20**	**25.87**	**43.06**	**38.72**	**39.94**	**40.61**
(%)	**SD**	4.93	12.74	15.38	13.83	14.27	4.94
	min	14.00	5.25	13.59	12.29	11.78	13.25
	Max	18.22	14.68	16.50	14.92	16.75	15.75
Wilting	**mean**	**16.86**	**9.24**	**15.38**	**13.83**	**14.27**	**14.50**
Point (%)	**SD**	1.76	4.55	1.25	1.08	3.51	1.76
Texture		L, SiL	SL, SiL	SiL, SiCL	SiL, SiCL	L, SiCL	SiL, SiCL

5. ASSESSMENT OF SEDIMENTATION BY EROSION

Land degradation is a persistent phenomenon in humid monsoonal Himalayan drainage system. The normal rate of which is a milestone for further analysis. This chapter deals this issue by describing the results of 'initial simulations', 'sensitivity analyses' of model outputs to input parameters, 'adaptations' on RMMF-daily erosion model and its performance. This also highlights the spatial erosion and depositional situation within the Andherikhola basin in a normal year.

5.1. Initial simulations

Initially, a number of simulations with minimum, maximum and mean values of soil parameters (see values in Table 4-2) were executed. As illustrated in Table 5-1soil loss was the least (i.e. 0- 2.60*10^8 tons/ha for daily basis and 89870 tons/ha for whole year) with 'maximum soil values' amongst three data sets. When in-stream erosion in higher (>3rd) order streams (based on 'Strahler stream order classification') was ignored, the annual loss abruptly dropped to 140 tons/ha.

Table 5-1: Daily and annual RMMF outputs in initial simulations

Sim**	Daily value ranges within whole watershed						
	Eta	Infill.	Disch.	Detach	TC	Deposition	Soil loss
1	0-162	0-1020	0-540000	0-2.8*10^8	1.76*10^{11}	0-36	0-2.8*10^8
2	0-162	0-890	0-540000	0-3.15*10^8	2.05*10^{11}	0-36	0-3.15*10^8
3	0-162	0-1080	0-540000	**0-2.6*10^8**	1.6*10^{11}	0-36	**0-2.6*10^8**
4	0-146	0-1080	0-540000	0-1980	1.6*10^{11}	0-36	0-1945
5	0-146	0-1080	0-540000	0-2.6*10^8	1.6*10^{11}	0-36	0-2.6*10^8
6	0-146	0-1080	0-540000	0-1980	1.6*10^{11}	0-36	0-1945

Sim**	Annual values/value ranges within whole watershed									
	Eta (mm)	Discharge (m^3)	Detach (ton/ha) F	H	Total	TC tons/ha	Depo. Range	Avg.	Soil loss (tons/ha) Range	Avg.
1	4600	52000	273	99727	100000	2.38*10^8	0-630	130	0-2.25*10^9	99870
2	4370	59000	273	119727	120000	2.90*10^8	0-620	115	0-2.65*10^9	119885
3	4600	48000	273	89727	**90000**	2.11*10^8	0-630	130	0-2.02*10^9	89870
4	4600	48000	258	11	269	2.11*10^8	0-630	129	0-12400	**140**
5	4600	48000	282	89718	90000	2.11*10^8	0-630	130	0-2.02*10^9	89870
6	4600	48000	258	11	269	2.11*10^8	0-630	129	0-12400	**140**

Annual average value ranges for land cover/use units						
Simulations	1	2	3	4	**5**	6
Deposition	0-156	0-148	0-160	0-156	0-160	0-156
Soil loss	0-4.25*10^7	0-5.0*10^7	0-3.85*10^7	**0-194**	0-3.85*10^7	**0-194**

** Simulations were made with (1) mean, (2) minimum, (3) maximum values of soil parameters, (4) maximum soil parameters and no in-stream erosion in >3rd order streams, and (5) a combined mean value of Ksat and maximum values of other soil parameters (6) conditions in 5 plus no in-stream erosion >3rd ordered stream.

And maximum soil loss per land uses has dropped to 194 from 3.85*10^7 tons/ha. However, these results are still very far from reality of the study area. Additionally, unlike others, the outputs have not changed when maximum Ksat was replaced by mean value (simulations 4 &6 in Table 5-1).

5.2. Sensitivity analysis

Sensitivity of different model products (e.g. discharge, transport capacity - TC, detachment, deposition, and soil loss) to major soil and vegetation parameters has provided fundamental clues for the operational improvement of RMMF-D erosion model to be applied in Andherikhola watershed. As illustrated in Table 5-2, total soil detachment, TC and soil loss have shown high sensitivity (Relative sensitivity-RS >1.0; Average linear sensitivity-ALS >1.0) to combined Ksat and porosity as well as effective hydrological height. These sensitivity indices are taken from Morgan and Duzant (2008) and Morgan (2005). The response of discharge has expressed moderate sensitivity (RS ≥ 0·5 < 1·0; ALS ≥ 0·5 < 1·0). The negative sign is the indication of inverse impact with the changes of Ksat and porosity values. Figure 5-1 also depicts the high sensitivity of discharge, TC and soil loss to porosity. But all outputs except TC have low sensitivity to Ksat when changes has made between minimum and maximum observed values. This model does not acknowledge the particular role of Ksat, indirect inclusion, however, is the high importance given to porosity and EHD. The synergic effect of BD (bulk density of top soil) and cohesion has visualised during the assessment, which shows the vital role of combined BD and cohesion via clear control to the detachment process. Furthermore, particular role of BD has found to be sensational for the runoff detachment (H) process; the RS and ALS values are above 1 as presented in Figure 5-2. Similar findings has reported by Jha and Paudel (2010) with the clear indication of not only high sensitivity of runoff detachment to BD but also to EHD. They also mentioned the remarkable sensitivity of TC to EHD in a middle mountain basin of Nepal.

Table 5-2: Values of relative sensitivity (RS) and average linear sensitivity (ALS) of various outputs of RMMF-D model for different input parameters (changes between ± 10% and ±20 % from base values)

	Relative sensitivity (RS)					**Average linear sensitivity (ALS)**				
	Ksat Poros	EHD	BD Coh.	SC	PH	Ksat poros	EHD	BD Coh.	SC	PH
Annual values at 10% changes from the base										
Discharge	-0.87	-0.86				-0.86	-0.85			
TC	-1.28	-1.09				-1.27	-1.11			
Total detach	-1.06	-1.11	-1.02			-1.04	-1.10	-1.01		
Splash detach				-1.14	0.70				-1.15	0.55
Deposition	0.48	0.54		-1.62	0.72	0.48	0.53		-1.62	0.57
Soil loss	-1.07	-1.11	-1.02			-1.06	-1.10	-1.01		
Annual values at 20% changes from the base										
Discharge	-0.97	-1.80				-0.85	-1.76			
TC	-2.62	-2.80				-2.53	-2.67			
Total detach	-2.12	-2.17	-1.00			-2.06	-2.09			
Splash detach				-1.34	0.58				-1.33	0.47
Deposition	1.01	0.92		-1.62	0.62	1.01	0.93		-1.59	0.50
Soil loss	-2.14	-2.22	-1.05			-2.06	-2.15			
Daily maximum values at 10% and 20% changes from the base										
	Ksat	EHD	Ksat	EHD		Ksat	EHD	Ksat	EHD	
	10%		**20%**			**10%**		**20%**		
Eta	-0.86		-1.03			-0.85		-0.89		
Infiltration	0.78	0.65	0.79	0.72		0.78	0.65	0.71	0.73	
TC	-1.08	-1.06	-2.16	-1.13		-1.07	-1.06	-2.09	-1.1	
Soil loss	-0.71	-0.77	-1.52	-1.63		-0.71	-0.77	-1.5	-1.62	

The solo contribution of cohesion, as revealed by Figure 5-2, on detachment process is also an important aspect for the RMMF model. Likewise, high sensitivity of detachment has noticed to SC but unlike BD it is splash disintegration (F) of soil particles. Moreover, splash detachment has shown moderate positive response to plants height (see numeric values in Table 5-2).

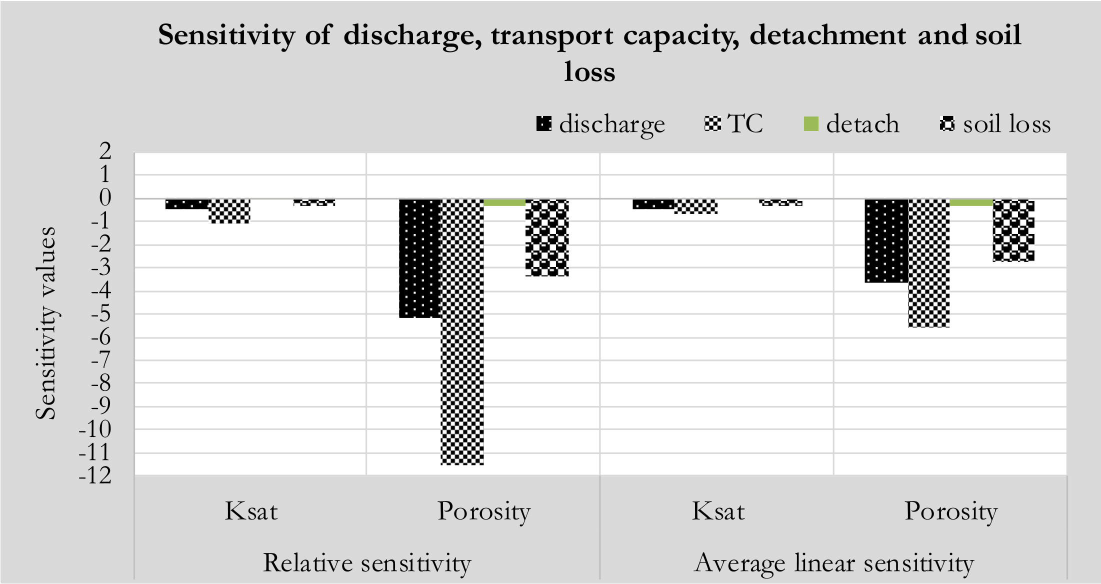


Figure 5-1: Relative, and average linear sensitivity of RMMF-D outputs to porosity and Ksat (variation between minimum and maximum observed values).

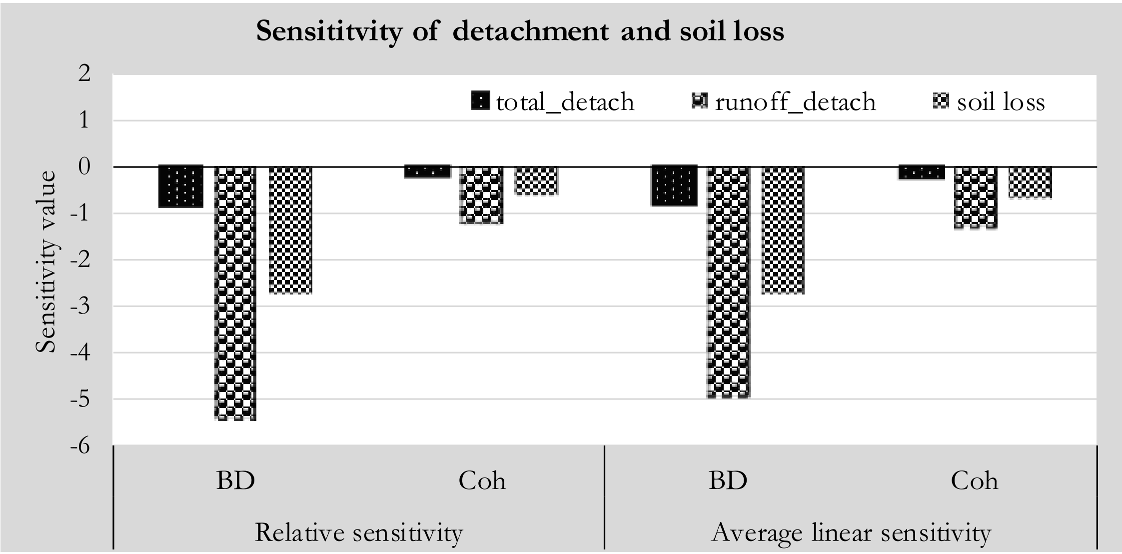


Figure 5-2: Relative sensitivity and average linear sensitivity of total and runoff detachment to bulk density and cohesion (variation between minimum and maximum observed values).

Looking into the daily maximum values (see Figure 5-2) TC has shown high sensitivity, whereas, ETa and soil loss have moderate response. The daily maximum infiltration showed positive moderate sensitivity to Ksat plus porosity and EHD.

5.3. Adaptations for Himalayan watershed

The pattern of relations of input parameters to the outputs as explained in **Section 5.2** together with evaluation results of NDVI values of all map series (summarised table in Appendix 8) has provided vital clues based on which seven different adaptive measures were identified for further tuning of the model (see sequential decision flow in Figure 5-3). The adaptive measures are categorised in two groups: (1) variation in sensitive input parameters, and (2) modifications in inclusion of spatial elements that bring changes to particular erosional processes.

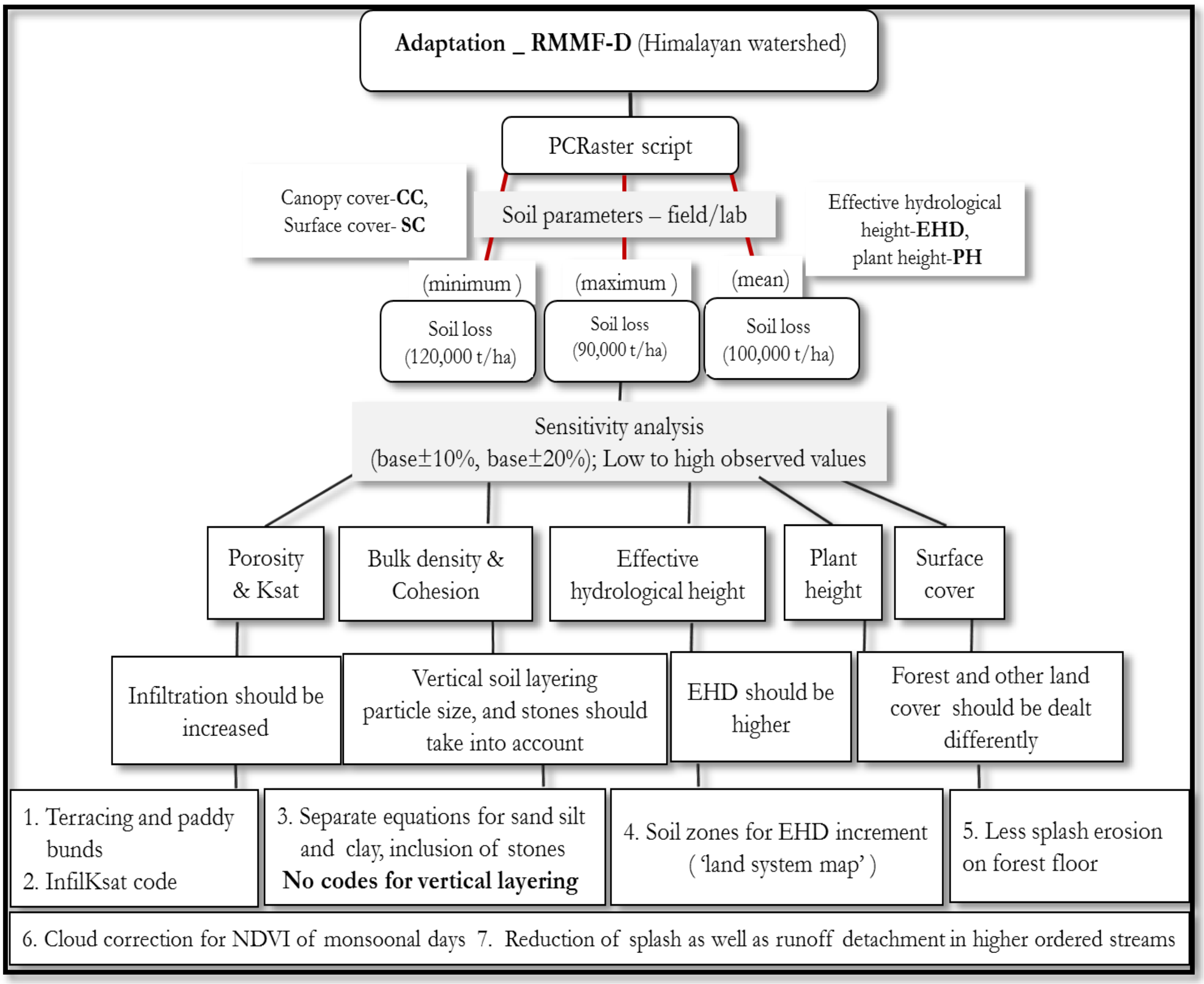


Figure 5-3: Decision flow to adapt the RMMF-D model for the middle mountain basins in the Himalaya.

Changes of EHD value, introduction of initial infiltration base followed by the calculation of runoff as a fraction of rainfall, 'cloud correction' for NDVI map series, 'separate detachments and transport capacity equations' for individual soil particle classes, inclusion of 'stone percent' are under former category. And the later includes 'Slope correction' to address local terraced farming practices, soil water 'storage increment' in view of about 15 - 20 cm bunds height in paddy fields, and inclusion or exclusion of higher ordered streams as an erosional element. Whereas consideration of 'less splash detachment' on forest floor is of intermediate kind, since it considers the importance of 'surface cover' on erosion process and also forest as a spatial unit.

Increment of 'EHD' value not only utilizing results of sensitivity analysis but also in view of the information of soil drainage that has provided by baseline soil map (GoN, 1985b) was made. But bearing in mind the importance of the top soil of few centimetres especially in erosion processes (e.g. providing surface cover, holding water and gradual supply for infiltration, preventing evapotranspiration during dry period), this study has considered the top 5 cm of soil profile. Ksat is a good indicator of physical process of downward movement of water into the soil profile, which deduct infiltration amount from runoff. But as mentioned in section 5.1, the RMMF model does not recognize the role of Ksat in such a way. While introducing initial infiltration base high observed Ksat value during lab analysis, knowledge about local precipitation patterns, and soil depth gave an idea to set threshold of rain duration and average soil depth that can pull water from the surface (soil depth was measured from 0.4 to 3m in the field wherever exposed soil profile was found, e.g. road cut slope, river bank, landslides area). The detachment and transport capacity vary for different sizes of particles since BD and cohesion differ accordingly. For instance clay and silt have high cohesion that demands more energy to be broken but when detached they are transported easily compared to sand. Thus inclusion of separate equations for individual textural class of soil is important. NDVI maps have been used to estimate cover (C) that affects the interception, and ET. Next, C has provided a factor to estimate SC which play role on detachment process. Whereas stony soil in one hand can reduce porosity, but stones as shown in Figure 5-4, protect soil against erosion.

Figure 5-4: Stones, protecting soil from being eroded like other (e.g. litter & ground vegetation) surface cover types.

The cultivation practices in middle mountains of Nepal always include terracing and if paddy is cultivated, bunds are for retention of irrigated water.

Figure 5-5: Terraced cultivation without and with bunds in rainfed and paddy fields in the south facing slopes of Andherikhola basin.

These terraces are artificial but very important spatial erosional elements which suddenly reduce slope and also increase temporary water storage during extreme rain events. It has implication to infiltration and transport capacity of accumulated flow (Figure 5.5).

The example outputs of the day-232 (20th Aug 2014) shown in Figure 5-6 depict how RMMF-D model works. With the complete ignorance of in-stream erosion when watershed received the effective rain -120 to 218 mm, infiltration has ranged from 0 to 366 mm; 0-4.77 mm water has lost by evapotranspiration. But it has generated maximum discharge of 540,382 m^3 and maximum transportation capacity of 252,323 tons/ha disintegrating 0-948 tons/ha soil within the watershed. Out of which spatial distribution of sedimentation has found to be between null and 136.38 tons/ha. The outgoing soil that is lost from the original hillslope was estimated between null to 94.8 tons/ha.

The resulting output after the integration of all aforementioned adjustments (slope correction – 1 degree for paddy fields and 4 degrees for rainfed and abandoned cultivation lands; 150 mm more water storage in paddy fields during heavy rainstorms; cloud correction - > 0.55 NDVI for peak growing seasonal days; limit

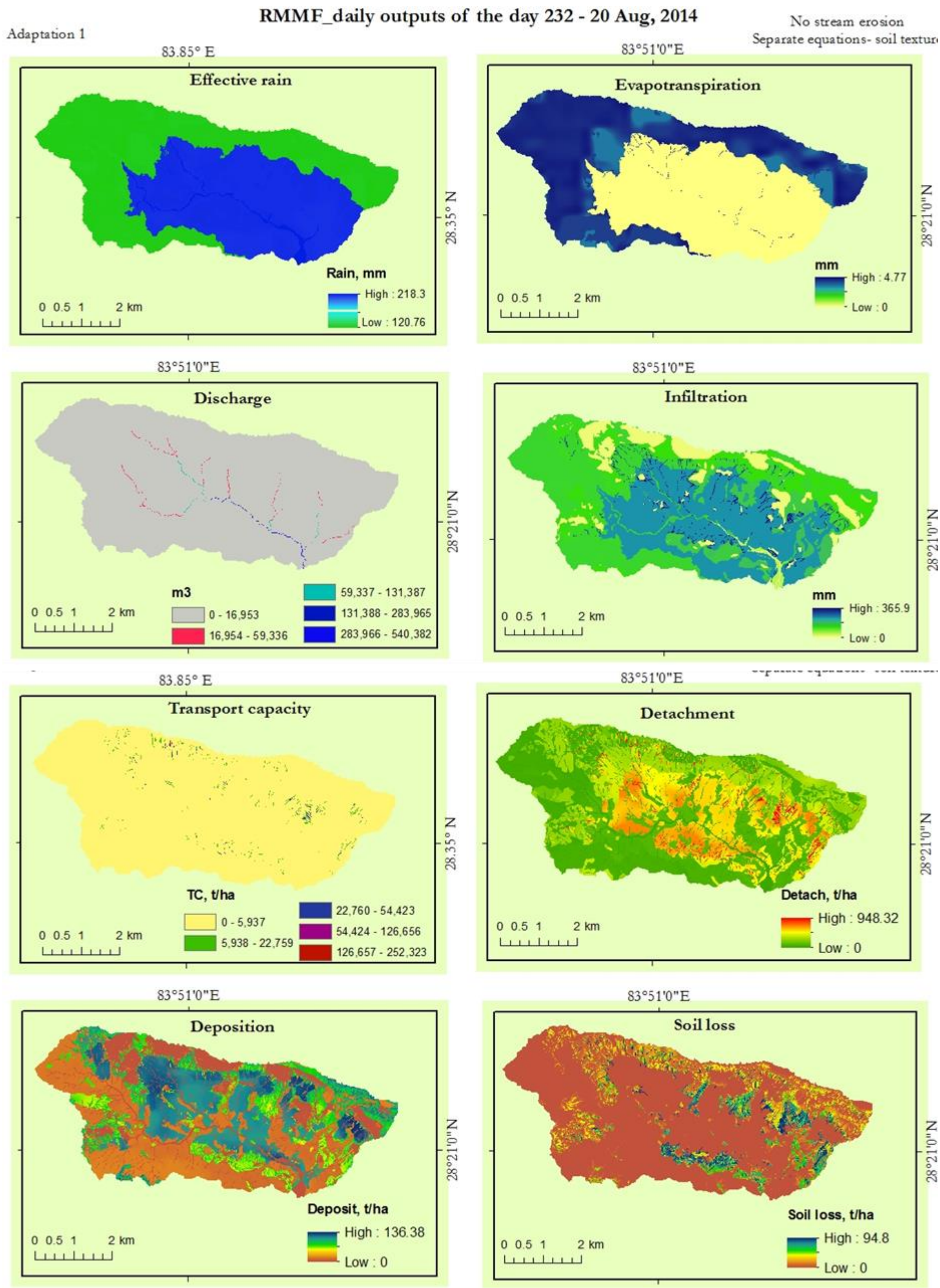


Figure 5-6: : Illustration of major daily outputs – effective rain, evapotranspiration, discharge, infiltration, transport capacity of runoff, spatial soil particle detachment, deposition and soil loss of RMMF-D erosion model, presenting day 232 (20 Aug 2014) as an example.

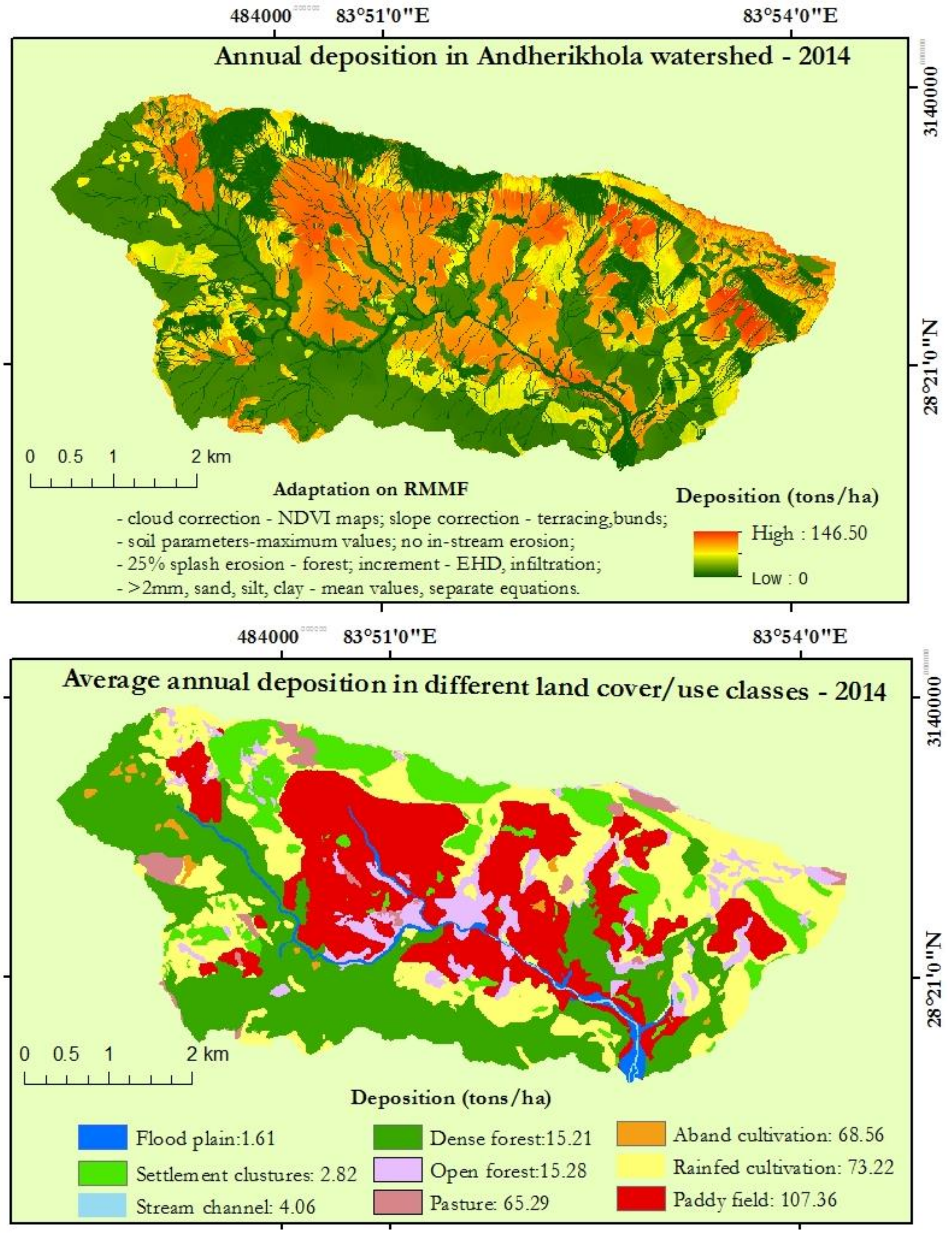


Figure 5-7: Spatial distribution of annual soil deposition (top) and annual average deposition per land cover/use class (bottom) for the base year 2014

of 25% splash detachment onto the forests floor; increment of EHD upto 0.10 – 0.35 m based on soil zone map; increment of infiltration base taking soil depth of 0.2 – 0.415 m and 2 hours rainfall duration; adjustment of detachment and TC rate by inclusion of observed mean values of stones and textural classes; and inclusion of maximum observed values of cohesion and BD) has shown close agreement to the study area (see Table 5-3 for modelling results).

The measured maximum values of BD and cohesion have taken during adaptation exercise (mean values for all other soil parameters) because (1) they perform well as shown in Table 5-1, (2) MMF model uses cohesion values of saturated soil but the 'soil shear strength' in this study has measured at normal in-situ moisture state, and (3) the SOM of top soil layer particularly in dense forest has found near to organic soil (see Table 4-2 and Appendix 9) with large fresh humic constituents. The degree of aggregation between OM and soil underneath was found to be low during field observation. Resultant effect was loose top soil layer that differ to the characteristics of dominant in-situ soil condition.

Out of the detached soil (69 tons/ha/y), 53 tons/ha/y has deposited within the watershed. Majority of soil breaking off has found by splashing (63 tons/ha). The deposition rate has ranged from 0- 147 ton/ha/yr within different units of the watershed. Paddy field has revealed as a high siltation area with great efficiency to trap the soil detached from the hillslopes - 107 ton/ha/yr. This role of paddy fields has also mentioned by Sthapit and Balla (1998) in a sedimentation study of Phewa watershed. Upland rainfed fields, abandoned cultivation land and pasture land have also shown a good potential of silt capture with the annual rate of 73, 69 and 65 tons/ha respectively. Both dense and open forest have held up 15 tons/ha soils annually. The flood plain has the least potential to settle down the transported soil from the upslope. It is because most of the detached materials deposited immediate after near the original slope and transferred materials to runoff in many occasions got settle down before reaching flood plain. Besides that, soil disintegration in floodplain itself is low and whole flood plain is flown over with sediment laden discharge during large flood events letting it capture the sediment but in normal days it does not happen.

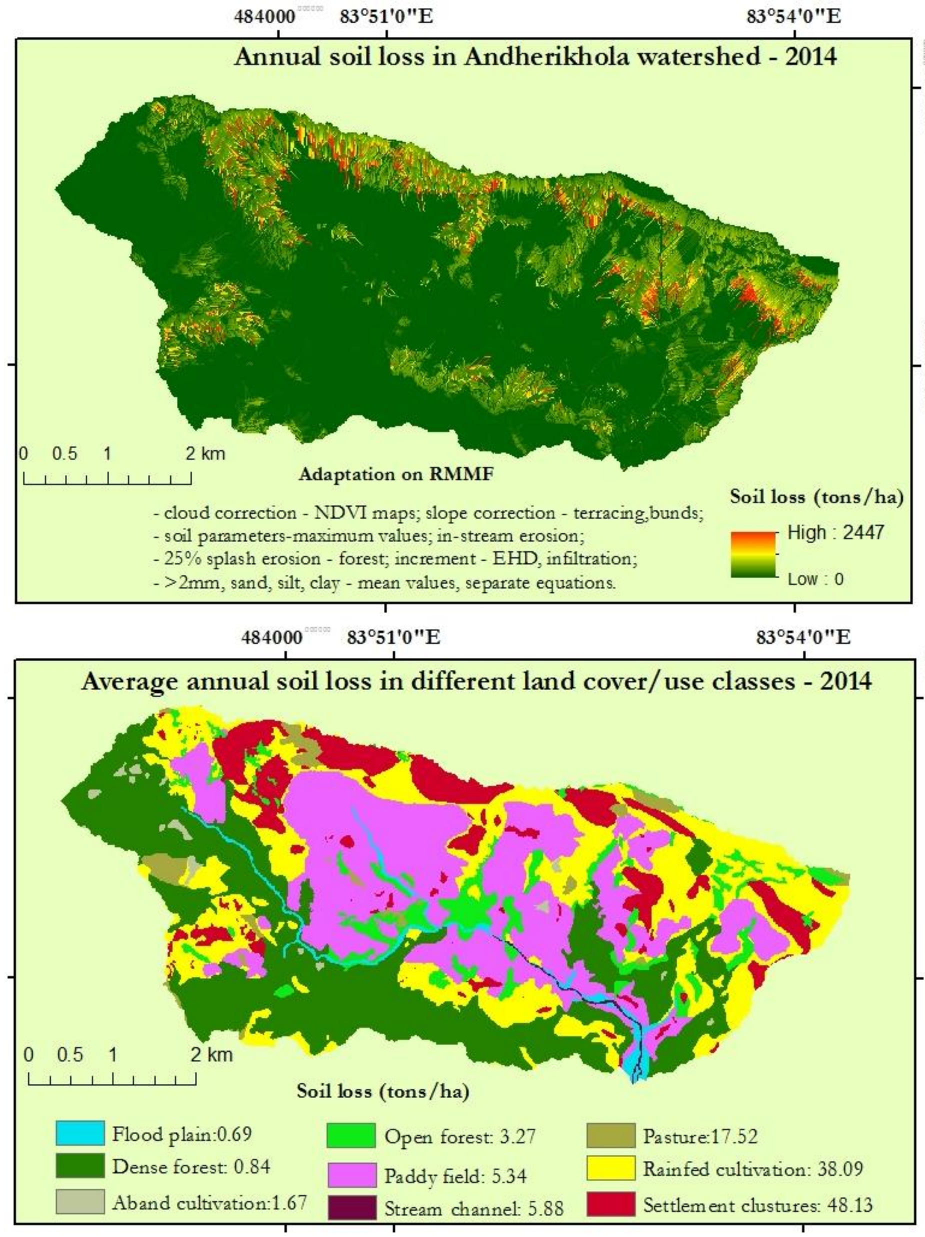


Figure 5-8: Spatial distribution of annual soil loss (top) and annual average soil loss per land cover/use class (bottom) for the base year 2014.

Annual soil loss from original hillslope was found to be between 0 and 2447 tons/ha. When looking into contribution by land cover/use classes, the highest one is the settlement cluster (48 tons/ha), followed by rain fed cultivation (38 tons/ha). Soil removal from open forest and dense forest was estimated 3.27 and 0.84 tons/ha. The results achieved by this set of amendment is near to the real situation. However, accumulated flow not only in rills and gullies but also in streams of higher order do contribute to normal erosion process.

Therefore, one more replication (now with inclusion of stream erosion) has been implemented. None of the separate equation for in-stream erosion has been applied, the assumption instead was made that mass wasting process in 'stream flow path' is alike to the process onto the hillslopes; the reason behind is the nature of RMMF model which is basically a runoff model and it does not comprehend instream erosion. The modelling exercise with this adaptation set has shown sudden elevated soil loss (up to $1.04*10^7$) and slight increment on deposition (see Figure 5-9 and Figure 5-10).

Unlike hillslopes, the stream flow paths especially in high gradient basins like Andherikhola, surface roughness of channel bed are very high (e.g. Figure 5-11). Boulders and coarse materials are dominant on flood plains. Without looking at this fact if simulation made, there is a risk of unrealistic prediction of sedimentation. In light of this viewpoint, reduplication was carried out with massive deduction (taking only 10% into account) of detachment rate inside the river network including flood plain. Now, annual soil loss reduces to 223 tons/ha with small change on deposition.

5.4. Model performance

The adaptive measures that have decided are based on pragmatic qualitative reasoning with emphasis on knowledge of the study area and pattern of sensitivity of erosional processes with input parameters instead of robust quantitative analysis. For the evaluation of model performance none of the observed data set is available for validation purpose. Thus, evaluation has made with (1) multiple simulations taking integrated adaptation set as a base, and (2) literature comparison. Assessment applying former approach has made to identify the implication of each adaptive measure in a sequence (see results in Table 5-3) as follows:

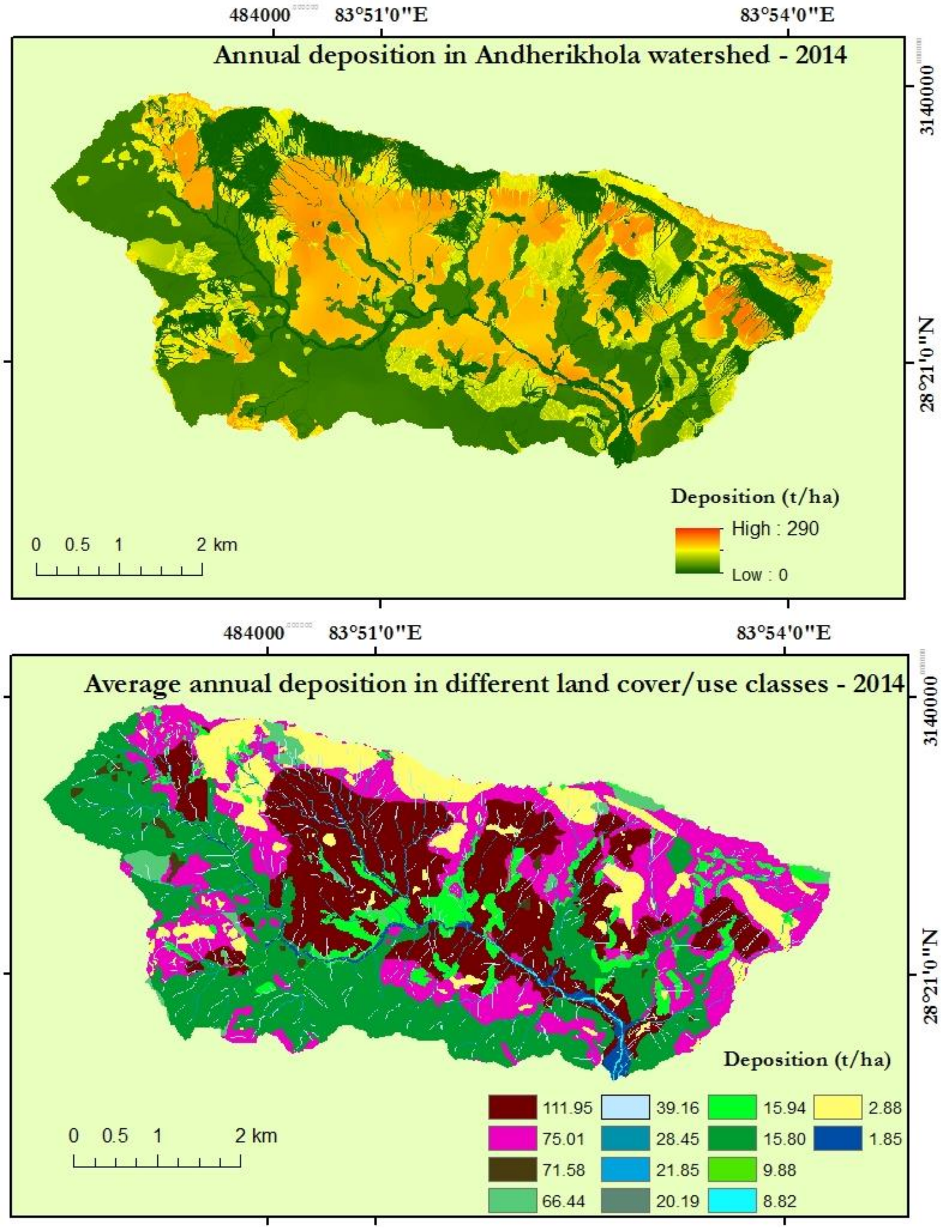


Figure 5-9: Spatial distribution of deposition with the inclusion of in-stream erosion for a normal year

1. Stream order: Considering the same erosional processes in streams that occur onto the hillslopes; no in-stream erosion in greater than 3rd order streams; and taking into account 10% detachments in streams of >3rd order (simulations 1-3).
2. Soil particle size: Separate detachment and transport capacity equations for sand, silt and clay; and ignoring response of separate soil particles in erosional processes (simulations 3 &4).
3. Slope correction for terracing and bunds: Disregarding terraces and bunds; giving consideration to terracing not bunds; and including both (simulations 5, 6 & 3).

4. Infiltration increment considering observed high Ksat values: Paying no attention on Ksat; introducing initial infiltration base which increased infiltration and reduces the runoff; and combining this with EHD guide values (simulation 7, 3 & 8).
5. Splash erosion in forest: taking no account of high surface cover in forest; assuming 50% splash detachment can be a real case; and limiting splash detachment to 25% (simulation 9, 10 &3).
6. NDVI cloud correction: taking no consideration of cloud effects; believing growing season NDVI not less than 0.5 in all area; and coupling this value to 0.7 minimum limit for forest (Simulation, 11, 12 &3).

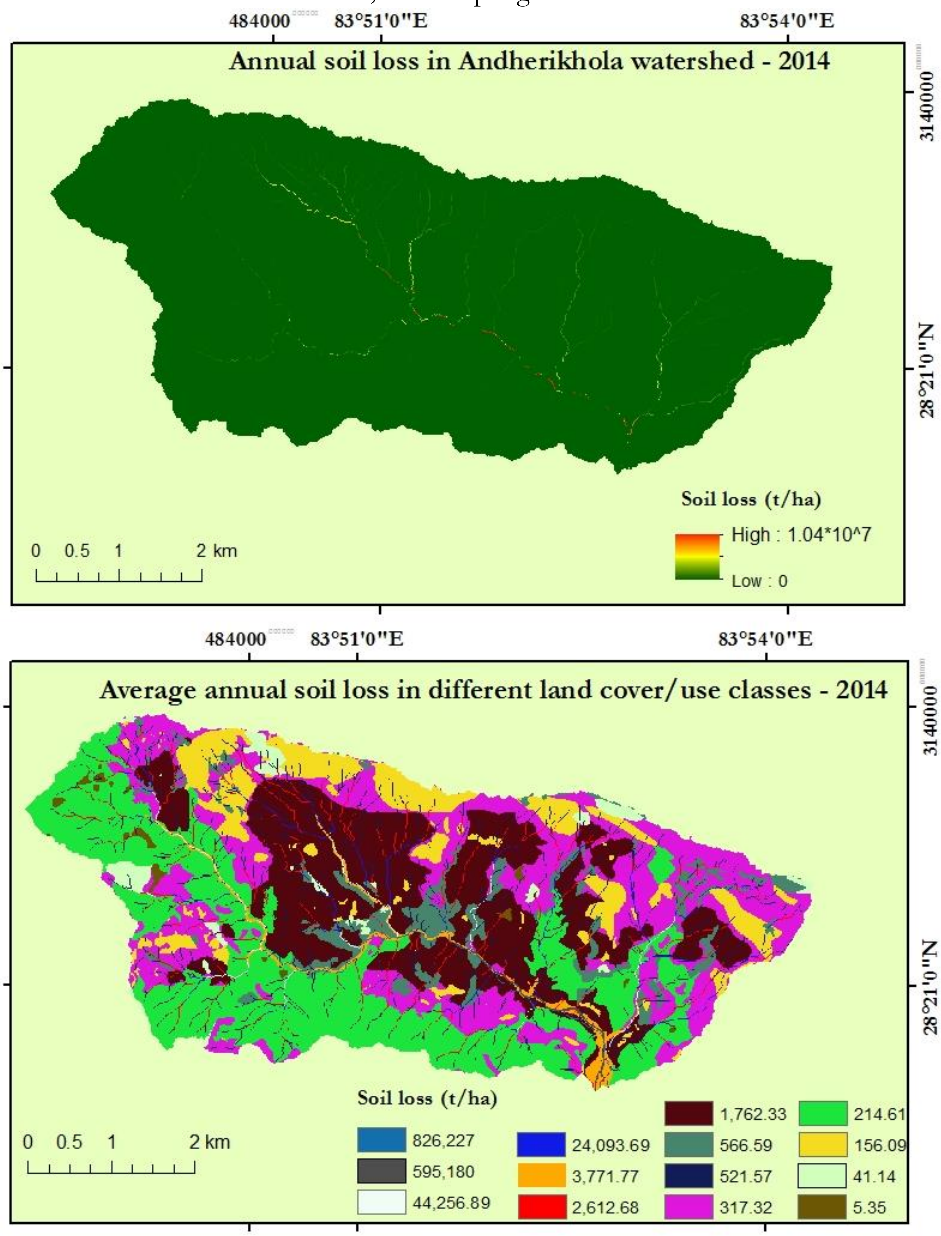


Figure 5-10: Spatial distribution of soil loss with the inclusion of in-stream erosion for a normal year.

'Simulation 3' as presented in Table 5-3 is the final modelling exercise of first part of aforementioned sequence i.e 'stream order' which was taken as a base for the anlysis of model performance.

The annual average soil loss has increased to 960 tons/ha i.e. 330% higher than the base (223 tons/ha) when individual equation for separate textural class was ignored. This is the indication of high implication of soil erodibility index (K) that is different to sand, silt and clay. As shown in Table 5-3, if reduced slope by terracing coupled with bunds is disregarded, the chance of over predicting soil loss is obvious i.e. 338 (51%) above the base. Similarly, the role of paddy fields (bunds are indicators) cannot be ignored because it can increase soil loss estimation by 50% when be disregarded. The role of Ksat is highly significant which could elevate soil loss calculation by 158 % if the code 'infilKsat' has not introduced during the adjustment process. The incremental EHD compare to guide value based on local speciality is another point to note because when EHD values brought back to guide values, soil loss has elevated from base value 223 to 395 tons/ha i.e. 77% higher than base. The impact of reduction of splash detachment onto the forest floor to ultimate soil loss has shown not so remarkable result. If prior screening applied during initial interpolation, further correction for growing season NDVI maps has also no significant changes on soil erosion research (2 % increment). By this results, it does not mean that 'C' factor has not sensational role for land degradation studies in Himalayan environment. This has particular impact on Eta and splash detachment (see results in Table 5-3, the daily maximum discharge has shown erroneous result because of another code that was preventing to report discharge values for each simulation, which was noticed afterwards).

Table 5-3: Daily and annual outputs of modelling exercises for each and integrated set of adaptation.

	Daily value ranges (maximum to minimum)						
Sim**	Eta (mm)	Infiltration (mm)	Discharge (m^3)	Detach (tons/ha)	TC (tons/ha)	Deposition (tons/ha)	Soil loss (tons/ha)
1	0-11.8	0-370	0-540000	0-260	0-9.5*10^{9}	0-16.2	0-246
2	0-11.8	0-370	0-540000	0-120000	0-9.5*10^{9}	0-45	0-120000
3	**0-11.8**	**0-370**	**0-540000**	**0-120000**	**0-9.5*10^{9}**	**0-16.2**	**0-120000**
4	0-11.8	0-370	0-540000	0-255000	0-1.16*10^{10}	0-23.5	0-255000
5	0-11.8	0-220	0-540000	0-166000	0-1.28*10^{10}	0-16.2	0-166000
6	0-11.8	0-220	0-540000	0-166000	0-1.28*10^{10}	0-16.2	0-166000
7	0-11.8	0-290	0-540000	0-395000	0-3.15*10^{10}	0-19.4	0-395000
8	0-11.8	0-370	0-540000	0-120000	0-1.98*10^{10}	0-15.2	0-120000
9	0-11.8	0-370	0-540000	0-120000	0-9.5*10^{9}	0-16.2	0-120000
10	0-11.8	0-370	0-540000	0-120000	0-9.5*10^{9}	0-16.2	0-120000
11	0-14.6	0-370	0-540000	0-120000	0-9.6*10^{9}	0-16.8	0-120000
12	0-11.8	0-370	0-540000	0-120000	0-9.5*10^{9}	0-16.2	0-120000

	Annual values/value ranges									
Sim**	Eta	Disch	Detach (ton)			TC	Depo. (tons/ha)		Soil loss (tons/ha)	
	(mm)	(m^3)	F	H	Total	tons/ha	Range	Avg.	Range	Avg.
1	480	120000	63	6	69	6.8*10^{6}	0-148	53	0-2450	16
2	480	120000	65	2065	2130	6.7*10^{6}	0-290	55	0-1.04*10^{7}	2075
3	**480**	**119000**	**63**	**213**	**276**	**6.8*10^{6}**	**0-148**	**53**	**0-1.04*10^{6}**	**223**
4	480	120000	176	934	1110	1.2*10^{7}	0-410	150	0-2.25*10^{7}	960
5	480	168000	63	326	389	1.07*10^{7}	0-148	51	0-1.66*10^{6}	338
6	480	169000	63	325	388	1.06*10^{7}	0-148	52	0-1.66*10^{6}	336
7	480	236000	63	560	623	2.38*10^{7}	0-156	46	0-2.90*10^{6}	577
8	480	178000	62	380	442	1.5*10^{7}	0-144	47	0-1.86*10^{6}	395
9	480	119000	80	212	292	6.8*10^{6}	0-148	69	0-1.04*10^{6}	223
10	478	119000	68	212	280	6.8*10^{6}	0-148	58	0-1.04*10^{6}	222
11	478	119000	69	215	284	7.0*10^{6}	0-235	57	0-1.06*10^{6}	228
12	466	119000	63.5	214	278	6.8*10^{6}	0-148	54	0-1.04*10^{6}	224

	Maximum and minimum annual average value ranges for - land cover/use class											
**Sim	1	2	3	4	5	6	7	8	9	10	11	12
Dep	0-108	0-112	**0-108**	0-285	0-104	0-104	0-106	0-108	0-108	0-108	110	0-108
Soil loss	0-48	0-8.3*10^{5}	**0-8.3*10^{5}**	0-4.5*10^{5}	0-1.3*10^{5}	0-1.3*10^{5}	0-2.35*10^{5}	0-1.52*10^{5}	0-8.3*10^{5}	0-8.3*10^{5}	0-8.3*10^{5}	0-8.3*10^{5}

** Simulations (1) adaptation with no in-stream erosion (2) including full in-stream erosion, explained in section 5.3. (3) 10% detachment on >3rd order streams including all other adaptations (4) disregarding different particle sizes (5) disregarding terracing and bunds (6) slope correction for terraces but ignorance of bunds (7) no attention on 'Ksat' (8) "infilKsat' plus EHD guide values (9) full splash disintegration of soils on forest floor (10) 50% splash detachment in forest (11) no cloud correction for NDVI maps & (12) no less than 0.5 NDVI during growing period.

To summarize, all adaptation measures that have chosen are incredible effects for reliable performance of model with an order of rank as follows:
Soil texture (in terms of K) > parameters that play role for infiltration other than soil texture (Ksat, EHD) > slope of the terrain >cover information.

Figure 5-11: High roughness on the stream bed, downstream of 'ratopahiro' inside the western part of the watershed.

The second and third simulation exercise of first sequence have extreme soil loss values which consider in-stream erosion (100 and 10%). This is obviously not acceptable for locals who know the ground reality. Thus the first simulation result i.e. with complete ignorance of stream erosion, with close agreement to the study area has been accepted for this research. This has estimated the average annual soil loss of 16 tons/ha which is comparable with the findings of Bhandari et al. (2015), who separated Andherikhola in two sub-watersheds viz. Andherikhola (20.8 km^2) and Thotnekhola (4.5 km^2) with estimated soil loss of 12.28 and 18.97 tons/ha/y.

However, Regmi and Saha (2015) had predicted soil loss 28.8 and 36.3 tons/ha for the year 2010 and 2015 respectively. Former estimation was by application of RUSLE and later had applied RMMF annual model. Pandey et al. (2009) indicated that MMF model over predicts soil loss in Himalayan watershed compared to USLE taking a case from Indian Himalaya. On the contrary, a study in a middle mountain Nepalese watershed had concluded RUSLE over predicts when the application made in an area larger than field scale (Jha and Paudel, 2010).

Regarding field plots experimental measurements, the soil loss from overgrazed and protected pasture within south facing northern slopes of the watershed had recorded as 34.7 and 9.4 tons/ha/y (Mulder, 1978). This study did not separate pasture land based on current practices because of low areal coverage. The soil loss in pasture has found higher i.e. 17.52 tons/ha/y compare to Mulder (1978).

In the identical plots of Mulder, Impat (1980) measured the earth moving downslope from its original land in the period of June to October, 1979 as 1.01, 9.85 and 0.43 tons/ha for protected pasture, overgrazed land and dense forest respectively. Current findings for dense forest (0.84tons/ha/y) is very close to his measurements. Furthermore, the sediment loss from open forest, abandoned cultivation, paddy fields and rainfed croplands has estimated as 3.27, 1.67, 5.34, and 38.09 respectively. The value for paddy fields is very high in comparison with Regmi and Saha (2015) - 0.3 ton/ha/yr. The value of their estimation is so because they considered only paddy fields close to the flood plains of whole Phewa watershed ignoring upslope large area under rice cropping. Even though, the loss of paddy cultivation is well above than reported by Shrestha et al. (2004) - < 1 tons/ha/y from a basin of similar environment. Whereas the rate of rainfed cultivation – 32 ton/ha/yr is somehow comparable to current finding.

6. SEDIMENT DELIVERY BY LANDSLIDES

Andherikhola as a whole behaved as a complex debris flow during massive mass movement incidence on 31 July, 2015. Many individual landslides had joined to the main channel; stream pathway had widened with considerable entrainment of materials while moving downstream from source to mouth. In this research, few representative cases of the debris flow initiation have been assessed to estimate the contribution of debris flows/landslides to the delivery of sediment to the main channel. This chapter provides brief explanation about the area that is covered by debris flows (runout), debris material initially released, and final deposits at the toes of each debris flows considered. It also further reveals the estimated sediment volume that has been injected to the main waterway.

6.1. Debris flow runout extent

In Figure 6-1, the initiation and runout area of the landslide incidences of 2015 are presented, covering total area of 540,000 m^2 (427388 m^2 has reached the river network) within the watershed. Comparison of pre (2014) and post (2015) event land cover/uses has revealed that the main stream channel of Andherikhola has been widened by 58% in post-event situation. The morphometry of considered debris flows, as summarised in Table 6-1, shows longitudinal shape with mobility index (H/L) of 0.3 for Damthiban, Thulachaur and Rudi debris flows and 0.5 for DF1. According to Iverson et al. (2015), although today's scientific understanding does not trust completely the picture that can be provided by H/L ratio (i.e. H/L<0.6 is taken as the indication of landslides that have longer distances), the practical applicability of

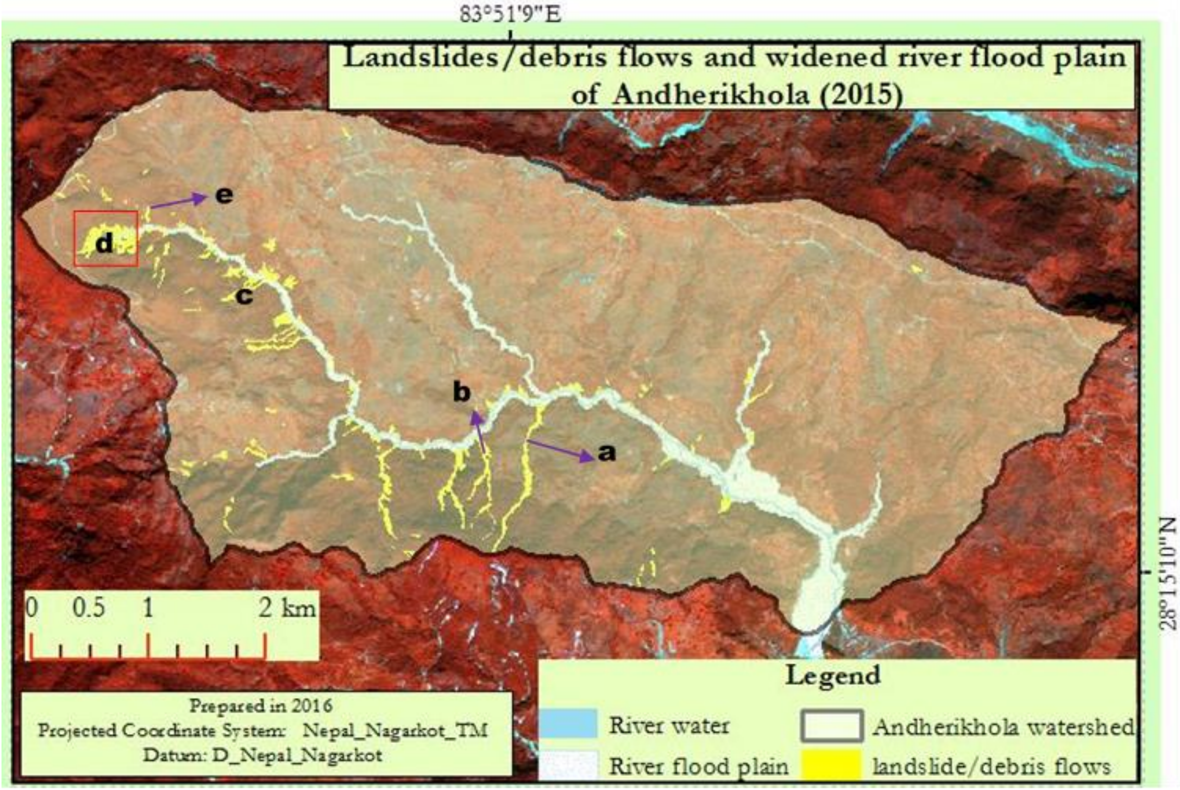


Figure 6-1: Andherikhola waterway as a complex debris flow (white) and location of individual landslides and debris flows initiation (yellow) mostly in south and western slopes including (a) Thulachaur, (b) Damthiban, (c) Rudi, (d) Ratopahiro, and (e) DF1.

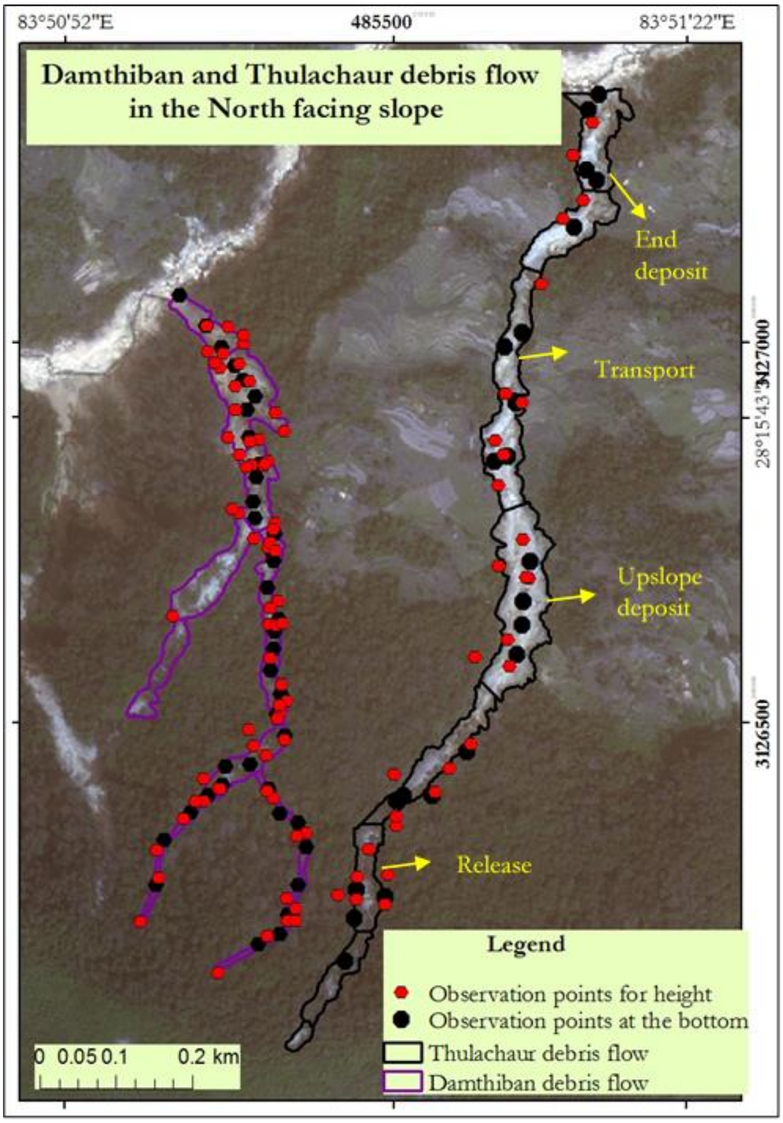
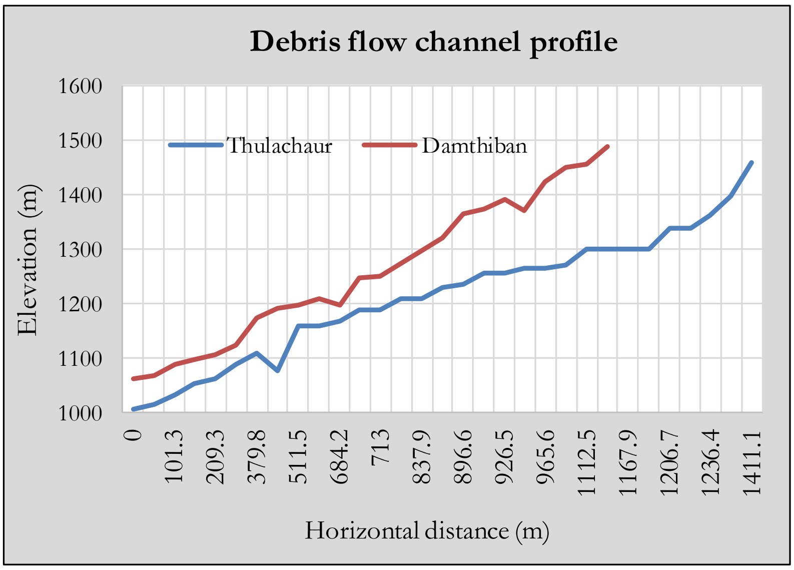


Figure 6-2: Runout extent of Damthiban and Thulachaur debris flows in the north facing slope of the watershed.



H/L ratio to gain initial notion of surface area that can be overflown by landslides is still valid.

Total areas affected by Damthiban, Thulachaur, Rudi and DF1 were estimated to be 35,997, 51,699, 16,415, and 4,196 m^2 respectively. Furthermore, if each zonal area presented in Table 6-1 ('release', 'transport' and 'deposit') converted to percentage coverage, Damthiban has 29, 40 and 31% respectively. Similarly, the areal percentage of each zone has found to be 29, 32 and 39 for Thulachaur; 20, 47 and 33 for Rudi; and 20, 71 and 9 for DF1.

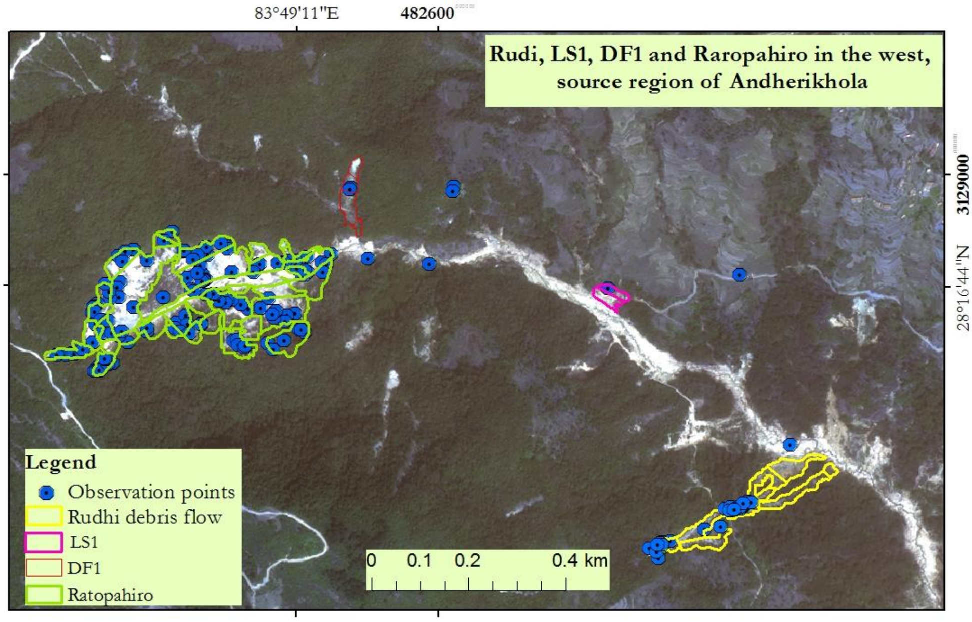
Of the studied debris flows Thulachaur (W_{avg}: 34.9 m; L_{tot}: 1372 m) is the longest and the widest and DF1 is the shortest.

Figure 6-3 elucidates the longitudinal channel profile of the Damthiban and Thulachaur debris flows. The continuous observations from debris flows scar to toe have elicited the cumulative horizontal distance and height for Damthiban and Thulachaur as 1120 and 426 and 1411 and 452 meters respectively. Because of some missing data channel profile for Rudi and DF1 debris flow are not included.

Figure 6-3: Channel profile of Damthiban and Thulachaur debris flows connecting the deepest parts starting from toe to the scar; the reference (zero elevation and HD) has taken the termination point of DFs to the river.

Ratopahiro landslide is a complex hillslope failure including debris slides in release zone in the west and rock falls and rock slides in the north and south slopes covering 84271 m^2 area. Many initiations and deposits were observed within a single landslide complex (Runout location is presented in Figure 6-1.

Unlike others, sediment has deposited immediate downslope onto the source zone of Andherikhola stream (i.e. zero or very short transportation zone). Average width and depth for 'release' and 'deposit' zones were measured to be 48 and 8 meters, and 69 and 14 meters respectively. The elevation range has recorded between 1628 to 1904 meters and local slope has measured between 8 and 65 degrees.



LS1, on the other hand is an example case of small landslides that ended up to the river. It covers 2261 m² area and has elevation difference only 6 meters with 24 meters of horizontal distance from toe to the scar.

Figure 6-4: Runout extent of Ratopahiro and LS1 landslides, and Rudi and DF1 debris flows.

Table 6-1: Morphometric summary of debris flows and landslides in Andherikhola watershed.

		Damthiban	Thulachaur	Rudi	DF1	Ratopahiro	LS1
Area (m^2)	Release	10606	14898	3257	836	33407	970
	Transport	14396	16464	7689	2990	50863	-
	Deposit	10995	20338	5469	370		1291
	Total	35997	51699	16415	4196	84271	2261
Width (m)	Min	7.2	19.7	3.4	11.3		54
	Max	67.2	58.2	35.6	31.9	48.3*	60
	Mean	28.6	34.9	22.0	22.9	69.4**	-
Depth (m)	Min	7.0	5.6	1.5	0.6		4.1
	Max	12.0	17.1	12.4	2.1	8*	1.2
	Mean	9.6	11.9	3.7	1.33	11.1**	-
Length (m)	Total	1293	1372	415	172		38
HD (m)	Total	1120	1411				23.8
Slope range (degree)		4-65	1-60	5-55	2-47	8-65	
Elevation range (m)		1061-1487	1005 -1457	1398-	1596-1682	1628-1904	1487-1493
Height (m)		426	452	138	86		6
L/H		3.0	3.0	3.0	2.0		6.33
H/L		0.3	0.3	0.3	0.5		0.2

HD: horizontal distance, L: length of debris flow runout, H: vertical height from termination points (toe) to the scar, L/H and H/L are debris flow mobility indexes, *: for release zone, **: for deposition zone

6.2. Sediment delivery to fluvial system

Debris materials released from 'scar', entrained on the way, and deposit as 'total' and 'end' deposit have estimated solely based on field observed data (Figure 6-2 outlines an example of separate zones considered). Four different mathematical models (see description in section 3.6.6) have applied to calculate area covered by debris flows and corresponding volume. In Table 6-2, Vol_1 is for 'planar area' Vol_2 is for 'triangular prism', Vol_3 is for 'parabolic' segment model and Vol_4 is ''rectangular prism. This table further provides measured values of materials volume that is initially released from failure zone (R), sediment that has been to originally released volume (entrainment –E), total deposit volume (TD) including upslope and end deposit (ED) and volume of debris injected to the river (IR) for each debris flows and Ratopahiro landslide. Fan deposit was observed for Damthiban, Thulachaur Rudi debris flows and LS1 landslide which was deducted from end deposit to find volume entered into the channel (Figure 6-5 clarifies fan deposit considered). Debris from DF1 has stopped just upslope the river channel, direct intrusion was not observed. Furthermore, triangular prism and parabola approach are not feasible for Ratopahiro and LS1 (Figure 6-6 outlines the location and associated complexity) and the released materials are also deposited immediate downslope area. Thus ED was supposed approximately equivalent to TD. The river polygon of land cover/use map was taken as a spatial unit and volume deposited onto it was accepted as IR.

Table 6-2: Debris volume that was released, deposited and injected into the river system of all considered debris flows/landslides, four different approaches (Vol_1: ArcGIS polygon section, Vol_2: triangular prismatic section, Vol_3: parabolic section, Vol_4: rectangular prismatic segment) were applied for volume estimation.

		Damthiban	**Thulachaur**	**Rudi**	**DF1**	**Ratopahiro**	**LS1**	**Remarks**
	Fan	17381	61042	795			1364	Vol_1: (ArcGIS polygon area*depth) Vol_2: triangular prism *length Vol_3: parabolic section*length
Vol_1	R	89785	158635	24624	1756	304659	3979	
(m^3)	E	150663	284552	14906	2194	315174		
	TD	240448	443187	39530	3950	619834		
	ED	157008	378079	1589	3580		3949	
	IR	139626	317037	795	$$	**606978**	2430	
Vol_2	R	52235	81320	13743	915			Vol_4: (length*width *depth)
(m^3)	E	77846	140156	575	644			
	TD	130081	221476	14317	1559			R: released
	ED	83149	192466	2459	1401			T: transported
	IR	**65767**	**131424**	**1665**				E: entrained
Vol_3	R	69647	108427	18324	1220			TD: total deposit
(m^3)	E	103794	186875	766	859			ED: end deposit
	TD	173441	295302	19090	2079			IR: injected into the river
	ED	110865	256621	3279	1867			
	IR	**93484**	**195580**	**2485**				
Vol_4	R	89785	162641	27486	1830	338046	4080	$$ Not entered directly to the river
(m^3)	E	177683	277521	6244	239	338212		#Not completely eroded on 2015 monsoon
	TD	267468	440161	33729	2070	641926	4080	
	ED	173604	382140	4919	1751		4080	
	IR	156222	321099	4124		# 631843	2716	

The sediment volume determined by aforementioned separate mathematical model gave different values and this was as expected. For, planar area and rectangular prism, 20% additional materials from transportation zone was assumed to be to the initially released materials, while estimating total and end deposits (Appendix 11 provides an example). But in case of triangular prism and parabolic section the materials volume within the transportation sections was supposed to be accumulated volume of earth originally removed from scar and entrained on the way. These assumptions were based on qualitative knowledge obtained during field exercise. Usually drainage channel are of v-shaped in middle mountains of Himalaya. But most of the DFs runout were observed as parabolic shaped. Uncertainty might have been introduced in the obtained results by many ways, for instance, many observations from the field have missed accurate height information because of the complex terrain and methodological error. The debris flow channel was very deep (Damthiban and also Thulachaur and in many places of Rudi) but in reality that was already a natural drainage channel. Gullies can be seen on topographic map and pre event satellite images. But no information was accessed how deep and wide the gullies were. This research did not pay attention to measure pre event gulley channel extent. The DEM that is utilized in this research is also of coarse resolution and it is based on 1990's data.

The past observed data sets of similar studies are really hard to access for comparison. And not all debris flows are easy to compare because the mass movement phenomenon for particular event has individual characteristics as a result of interaction of combined site specific variables.

Figure 6-5: Entry location of Damthiban debris flow into main channel of Andherikhola indicating a clear demarcation of mainstream materials.

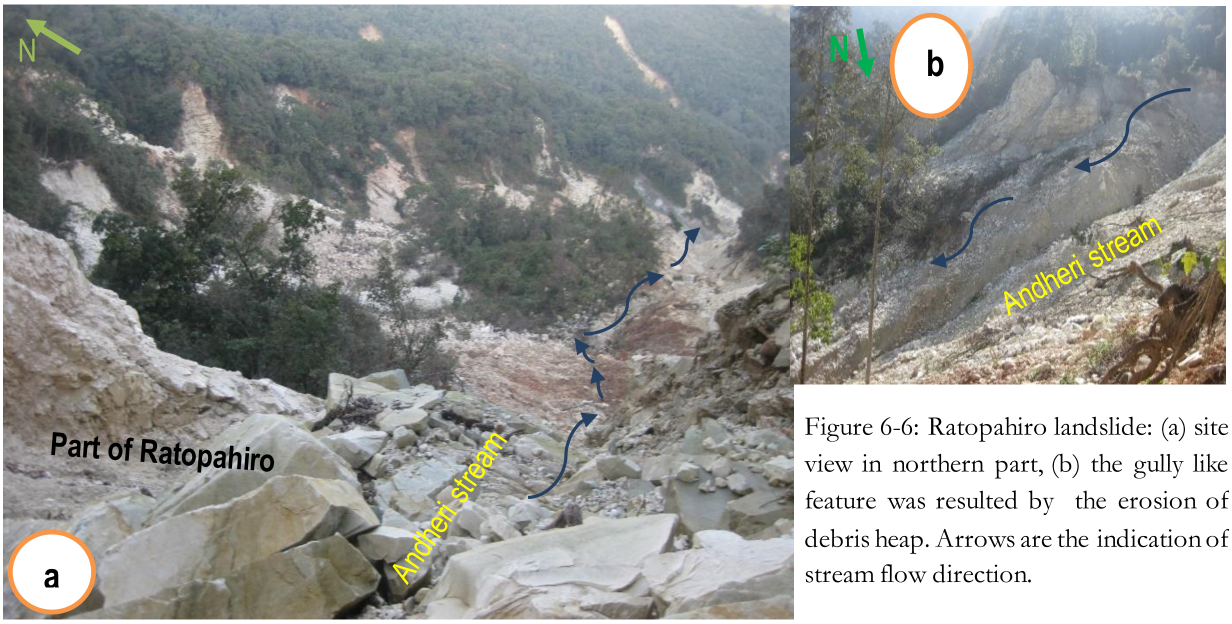


Figure 6-6: Ratopahiro landslide: (a) site view in northern part, (b) the gully like feature was resulted by the erosion of debris heap. Arrows are the indication of stream flow direction.

However, the morphometric and volume estimations have also been compared with those of three landslides (i.e. Paudur, Bhadaure Deurali and Kaskikot) considered in an earlier study by Ramsay (1985) Comparison of the Ratopahiro landslide of this study with the earlier Paudur landslide (that also occurred in the NW part of Andherikhola watershed) shows a number of differences (see summary in Appendix 12). Ratopahiro landslide is deeper and has a scar area that is 32% bigger, its total area is almost double, the total volume is four times bigger and the slope also varies from 8-65 degrees in comparison with the 5-35 degrees of Paudur landslide. Comparison of a big debris slide in Bhadaure Deurali (Ramsay, 1985) with the Damthiban and Thulachaur debris flows of this study shows that the recent debris flows each are smaller in dimensions and have produced less volume of debris. Kaskikot shallow slide (Ramsay, 1985) and DF1 debris flow of this study show that DF1 has higher scar area (11%), total area (52%), length (56%), maximum width (6%) and volume quadrupled; slope is also steeper than Kaskikot slide. But as shown in Table 6-3, the Pearson correlation of debris volume of this study with Ramsay (1985) shows strong positive correlation when Ratopahiro landslide excluded. Ratopahoro landslide is really huge that's why it has substantially high volume compared to others. Furthermore scatter chart of area vs volume, as shown in Figure 6-7 shows a resemblance of findings of this study to Ramsay (1985).

Table 6-3: Pearson correlation between debris volume and V/A ratio of landslides of this study and (Ramsay, 1985)

	Area		Volume		V/A		
	This study	Ramsay	This study	Ramsay	This study	Ramsay	
Thulachaur	51699	132000	236048	730000	4.6	5.5	Paudur
Ratopahiro	84271	42000	619834	126000	7.4	3.0	Bhadaure Deurali
LS1	2261	2750	3949	975	1.7	0.4	Kaskikot
r^2	**0.41**		**0.02**		**0.51**		
Damthiban	35997	42000	157008	126000	4.4	3.0	Paudur
Thulachaur	51699	132000	236048	730000	4.6	5.5	Bhadaure Deurali
Rudi	16415	2750	39530	975	2.4	0.4	Kaskikot
r2	**0.96**		**0.89**		**0.91**		
Damthiban	35997	42000	157008	126000	4.4	3.0	Paudur
Thulachaur	51699	132000	236048	730000	4.6	5.5	Bhadaure Deurali
LS1	2261	2750	3949	975	1.7	0.4	Kaskikot
r^2	**0.91**		**0.86**		**0.90**		

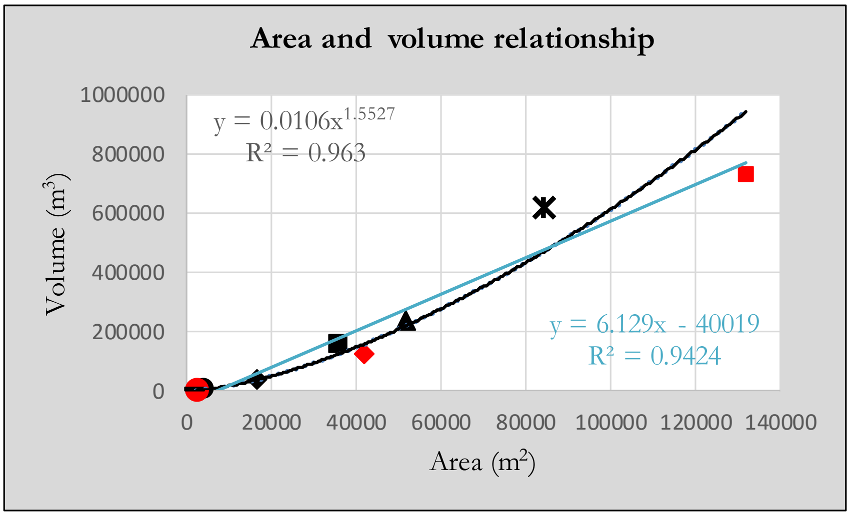


Figure 6-7: Analysis of volume and area relationship of debris flows/landslides; the red coloured points are from Ramsay (1985) and black ones are of current study. Different patterns of points are for different debris flows/landslides studied.

Out of four volume estimation approaches, though correlation coefficient of originally released debris to entrain and all deposits (correlation analysis results are presented in Appendix 13) was above 0.91 for all model results, considering general pattern i.e. 'v shaped valley' of drainage channel in middle mountains and parabolic shape observed in the field in most of the runout path for each debris flows either 'triangular prism', or 'parabolic segment' model are accepted (Table 6-4). Similarly, although 'rectangular prism' is a simple and common model to be used, for complex as well as small landslides planer areal (i.e. digitised polygon) segment was chosen as a better estimation approach.

Table 6-4: Volume measurement approaches applicable to debris flows and landslides.

Volume estimation approach	Damthiban debris flow	Thulachaur debris flow	Rudi Debris flow	Ratopahiro landslide	LS1 landslide
Triangular prism	65767	131424	1665		
Parabolic segment	93484	195580	2485		
Planar areal segment				606978	2430

7. NET SEDIMENT CONTRIBUTION BY LANDSLIDES INTO FLUVIAL SYSTEM

The main focus of this chapter is to answer what volume of sediments has been supplied to fluvial system by landslide events on 31 July 2015. It presents results of comparative analysis of erosional processes of 2014 and 2015 to see either the incremental soil loss is achievable for 2015 by the inclusion of recent landslides area as a bare surface. In addition, results of finer component out of total debris volume that has been directly intruded by landslides to the river system and the total fine sediment that has been transported downstream from the watershed are also dealt.

7.1. Incremental sedimentation by erosional process

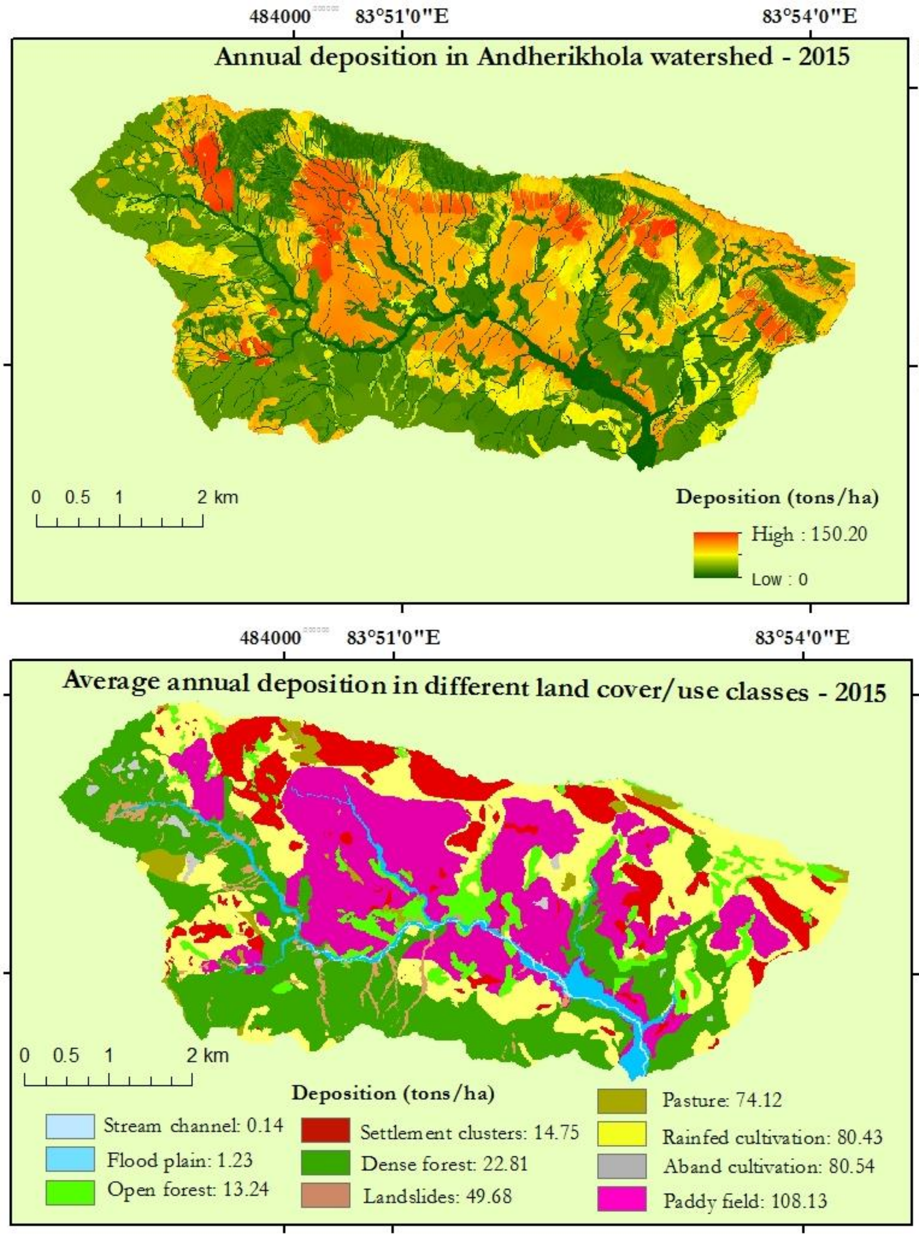


Figure 7-1: Spatial distribution of annual soil deposition within the catchment (top) and within land cover/use units in post landslides situation.

Assessment of incremental soil loss for the aftermath landslide situation i.e. for 2015 was performed by comparing the outputs of RMMF-D erosion model of the normal annual base value i.e. of 2014. The area that has been affected by recent mass movements (54 ha) was included as bare surface for the 2015 situation whereas small area (3 ha) that was covered by landslides in 2014 was labelled as land cover of surrounding area. For example, few smaller landslides that had occurred in 2014 (lies within the Ratopahiro of 2015) were kept under dense forest because those landslides (also Ratopahiro) lie within intact dense forest. Unlike permanent bare surface it was considered as bare land with loose materials. The results of this comparison are presented in Table 7-1. Both daily maximum detachment rate and annual average values are higher compared to 2014. The annual average soil deposition in 2015 was found to range between 0 and 150 tons/ha (see Figure 7-1 for spatial distribution of soil deposition). The pattern is similar to base year 2014 e.g. comparable higher deposition in northern slopes than in southern step hills. In addition, depositional pockets onto the debris flows and landslides area has been seen as expected. The average deposition per land cover/use units also shows a similar pattern to the normal year 2014. The values of deposition of originally removed sediments and soil loss were observed to be increased in dense forest, settlement clusters, pasture and abandoned cultivation. And many new higher soil loss spots in southern slopes compared to surrounding land cover were developed (see spatial soil loss distribution in Figure 7-2). The incremental soil loss was found to be 1 tons/ha/y.

Cumulative soil loss as elucidates by Figure 7-3 for the base year 2014 and landslide disaster year 2015 were obtained as 51013 and 66383 tons for whole catchment with effective rain as shown in Appendix 14. Furthermore, as Table 7-2 presents average sedimentation rate in tons/ha and sediment volume in cubic meters also shows incremental trend in most of the land cover/use units. Whereas the deduction was observed in open forest, flood plain and main stream channel. Slight decrement of soil loss was also detected in paddy and rainfed cultivation. Seeing this result a sceptic view can arise because the area covered by landslides i.e. 0.54 km² in a watershed of 27 km² may not be sufficient enough to raise soil loss with this extent. Daily maximum rain was 95 mm higher in 2015 than the previous year. It is obvious this rain would enhance normal rate of erosion but contribution of

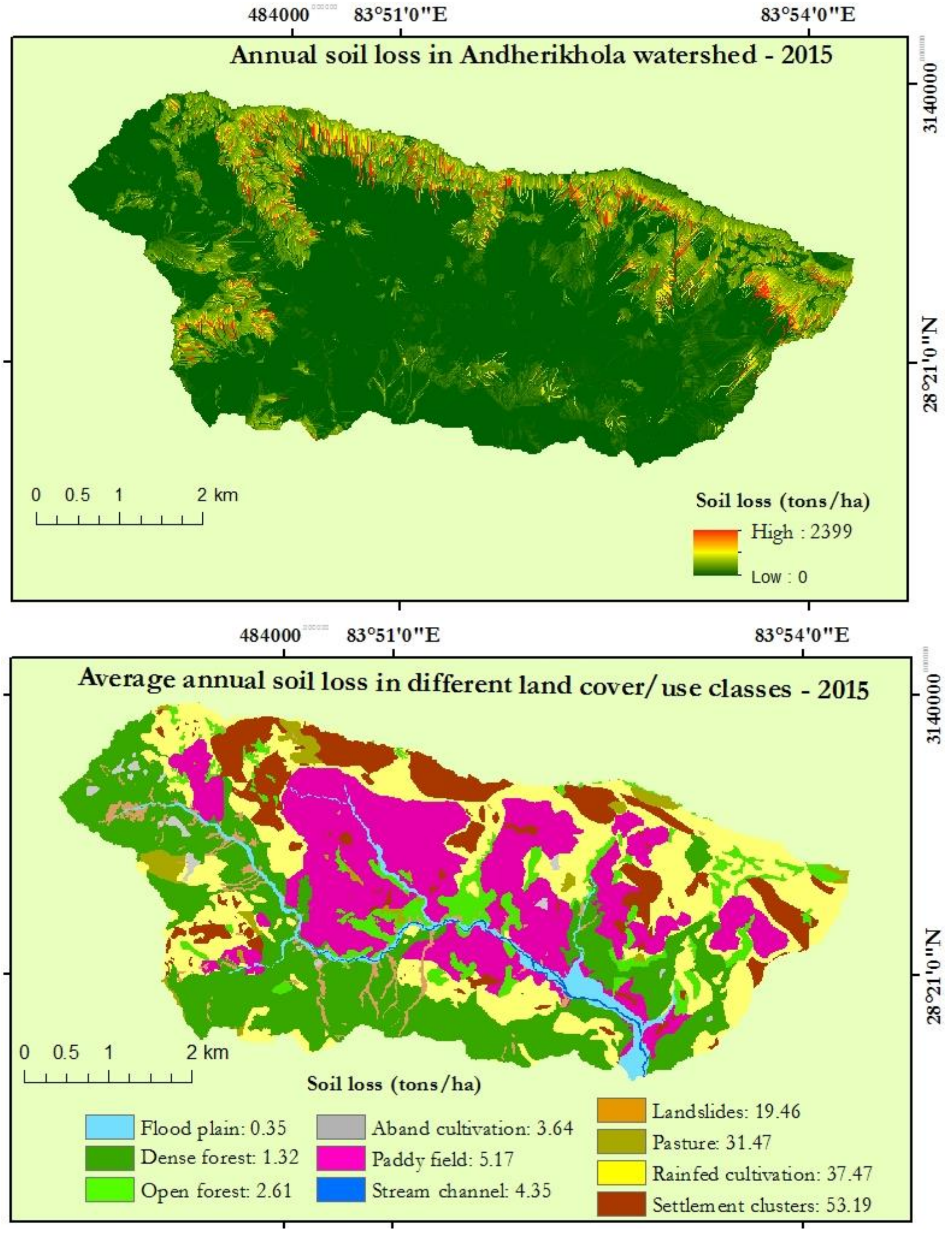


Figure 7-2: Spatial distribution of annual soil loss within the catchment (top) and within land cover/use units in post landslides situation.

additional bare surface in this high rainfall situation cannot be ignored. However, finding a straight answer of abrupt increment of soil loss in pasture is pressing. It demands further research digging into the combined effect of parameters.

Table 7-1: Daily and annual values/value ranges of RMMF-D outputs (e.g. effective rainfall, detachment, transport capacity, discharge, deposition and soil loss) for base year, 2014 and post landslide year, 2015.

Sim**	Daily value ranges within whole watershed						
	Eta (mm)	Infiltrat (mm)	Discharge (m^3)	Detach (tons/ha)	TC (tons/ha)	Deposition (tons/ha)	Soil loss (tons/ha)
2014	0-11.8	0-370	0-540000	0-260	0-9.5*10^9	0-16.2	0-240
2015	0-13.6	0-860	1.4 * 10^7	0-520	0-4.75*10^{10}	0-12	0-513

Sim**	Annual value /value ranges within whole watershed									
	Eta	Disch	Detachment (ton/ha)			TC	Depo. (tons/ha)		Soil loss (tons/ha)	
	(mm)	(m^3)	F	H	Total	tons/ha	Range	Avg.	Range	Avg.
2014	480	120000	63	6	69	6.8*10^6	0-147	53	0-2450	16
2015	480	110000	68	7	75	7.51 *10^6	0-150	58	0-2399	17

Table 7-2: Comparative summary of soil deposition and loss for the pre and post landslides event situation i.e. for the year 2014 and 2015.

	Deposition 2014		**Deposition 2015**		**Change**		**Soil loss 2014**		**Soil loss 2015**		**Change**	
Land unit	tons/ha	m^3	tons/ha	m^3	tons/ha	m^3	tons/ha	m^3	tons/ha	m^3	tons/ha	m^3
Dense F.	15	8409	23	11813	8	3404	1	464	1	684	1	220
Open F.	15	1921	13	1618	-2	-303	3	411	3	319	-1	-92
Paddy	107	53450	108	51672	1	-1778	5	2659	5	2471	0	-188
Rainfed	73	31380	80	34067	7	2687	38	16324	38	15911	-1	-414
Pasture	65	2798	74	3177	9	378	18	751	32	1349	14	598
Aband. Cultivation	69	833	81	978	12	146	2	20	4	44	2	24
Settlement	3	558	15	2918	12	2360	48	9523	53	10525	5	1002
Flood plain	2	61	1	74	0	13	1	26	0	21	0	-5
Stream	4	9	0	1	-4	-8	6	13	4	34	-2	22
LSs		0	**50**	1916	50	1916		0	**20**	751	20	751

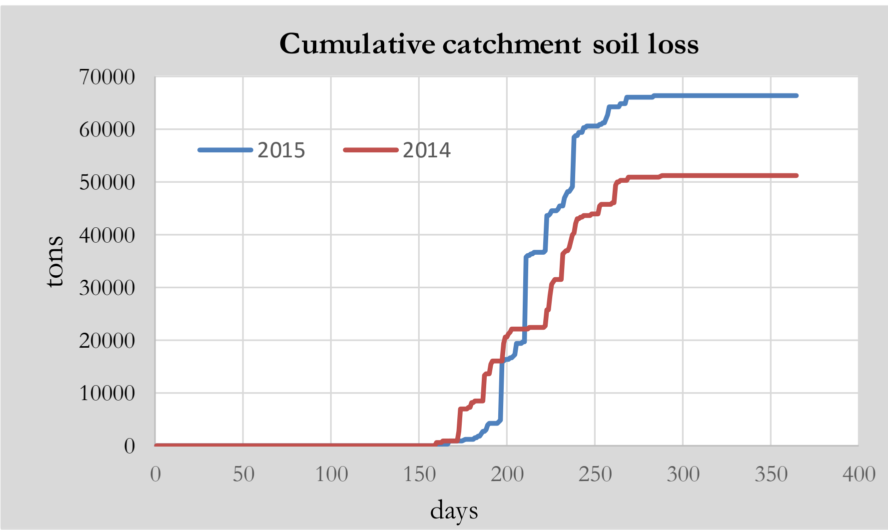


Figure 7-3: Cumulative soil loss of Andherikhola basin for the base year 2014 and the year 2015.

The sediment flux for base year as well as year of landslide disaster i.e. 16 and 17 tons/ha/y are within the range (1.73 to 37 tons/ha/y) reported by West et al. (2015) which was based on analysis of past studies (n=8, ±68 confidence interval) of catchments in middle hills of Nepal. This shows wide range of sediment fluxing which can be because of spatial diversities or methodological inconsistences.

7.2. Direct sediment delivery by landslides

The proportion of fine component (i.e. <2mm) as a lump volume and also the individual volume (five groups: 1-2, 0.5-1, 0.25-0.5, 0.125-0.25 and <0.125 mm) for different particle size class (see values for each debris flow and landslide in Appendix 15 that has obtained by gradation analysis) is the basis for estimation of net contribution of fine soil to the river system by each debris flow/landslide. This volume of fine material can be transported downstream by stream discharge with high transport capacity. The gradation values of Damthiban debris flow were also applied to Rudi debris flow since field measurement data for it are missing and the parent materials are similar (Phyllite and intercalation of quartzite in between) in both cases. Similarly, particle size results from DF1 debris flow were applied to LS1 landslide which lie nearby.
Table 7-3 summarises the proportion of coarse i.e. >2 mm and fine i.e. <2 mm sediment. The coarse component includes the size up to 16 mm while the fine component further split to five different texture classes up to 0.125 mm (i.e. fine sand). While calculating percentage of fine component (i.e. <2 mm) from the total debris volume, the percentage of coarse component (i.e. >2mm) was supposed to be equivalent to the total earth materials injected into the river (meaning including boulders). This study did not estimate boulder percentage separately. Therefore the uncertainty of estimation can be higher if percentages of finer constituent either come down or goes up when boulders also included in the estimation.

Table 7-3: Proportion of fine earth as a lump volume (< 2mm) and individual volume of five finer categories of sediment particles that has injected to main channel of Andherikhola from each debris flow and landslide considered.

		Damthiban debris flow	Thulachaur debris flow	Rudi debris flow	Ratopahiro landslide	LS1 landslide
Volume injected to river		**93484**	**195580**	**2485**	**606978**	**2430**
	<2mm	31897	63966	848	**206979**	826.2
Vol_A*	1-2mm	7198	13182	191	41760	388.8
(m^3)	0.5 -1mm	5796	7960	154	37936	194.4
	0.25-0.5 mm	5057	12498	134	46859	97.2
	0.125 – 0.25 mm	3506	11539	93	53414	97.2
	<0.125 mm	10377	18521	276	27011	48.6
Volume injected to river		**65767**	**131424**	**1665**	**631843**	**2716**
	<2mm	22440	**42984**	568	215458	923.44
Vol_B**	1-2mm	5064	8858	128	43471	434.56
(m^3)	0.5 -1mm	4078	5349	103	39490	217.28
	0.25-0.5 mm	3558	8398	90	48778	108.64
	0.125 – 0.25 mm	2466	7754	62	55602	108.64
	<0.125 mm	7300	12446	185	28117	54.32

* **'Parabolic segmentation'** for debris flows and **ArcGIS polygon segment** for landslides.
'Triangular prismatic segmentation'** for debris flows and **'rectangular shaped segmentation'** landslides.

Out of total sediment that has entered into fluvial channel, the lumped volume of finer component i.e. of <2mm and <0.125 mm (<0.125 mm was not further analysed to estimate fine sand, silt and clay particles, therefore it is taken as lumped volume of the finest particles) and intermediate classes in between i.e. from 2 mm to 0.125 mm, Thulachaur has contributed the highest volume amongst debris flows. The contribution of complex landslide - Ratopahiro is massive. The content has completely swept away by streams that has received by all debris flows/landslides except Ratopahiro. The heap of finer constituent assembling with coarse components of sediment is still onto the river valley in case of Ratopahiro (see Figure 6-6).

Initially, with the aim of determination of time required for complete washing off of the debris deposited onto the river by water discharge, spatial area that debris had occupied inside the river channel was delimited (red pixels in Figure 7-4). The plan was one more duplicating simulation after putting the values of debris volume to the pixels identified as debris receiving cells. However, because of RMMF erosion model's structure the erosional processes have to be limited to 'no channel erosion' scenario (detail explanation in chapter 6) which has prevented to accomplish this task.

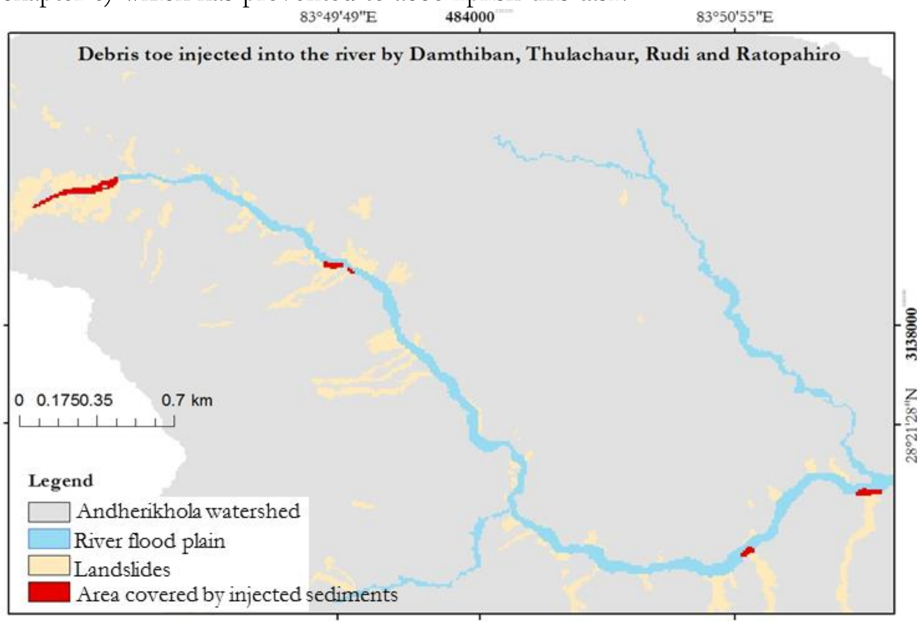


Figure 7-4: Delineation of approximate area inside river valley that had occupied by the bulk of sediments from landsliding on 31 July 2015.

The sediment volume by erosion process i.e. 36438 m^3 for 2014 and 47417 m^3 for 2015 (calculated dividing accumulated soil loss as plotted in Figure 7-3 by average bulk density) are less than finer sediment volume contributed by Thulachaur debris flow as well as Ratopahiro landslide separately (estimated volume is presented in Table 7-3). The contribution of Thulachaur DF is also close to base year sediment yield.

The results of total and fine constituents' volume obtained for DFs/LSs considered were extrapolated to other resembling cases (see grouping of landslides for extrapolation in Figure 7-4 and Table 7-4 for estimated sediment volume for each group). Though, Damthiban group includes only three debris flows because of larger dimensions, its contribution is remarkably high compared to others.

Table 7-4: Approximate total contribution of fine sediments (<2mm) by landslide incidences of 2015 that directly fed to Andherikhola main channel.

		Damthiban group	Rudi group	LS1 group	Remarks
Volume injected to river		**280452**	**9940**	**53460**	Debris flows in Damthiban group = 3
	<2mm	95691	3392	**18176**	Debris flows in Rudi group
Vol_A*	1-2mm	21594	764	8554	= 4
(m^3)	0.5 -1mm	17388	616	4277	Small landslides in LS1 group = 22
	0.25-0.5 mm	15171	536	2138	(including each observed case within
	0.125 -0.25 mm	10518	372	2138	particular group)
	<0.125 mm	31131	1104	1069	
Volume injected to river		**197301**	**6660**	**59752**	**IR=** total volume of sediments (big
Vol_B**	<2mm	**67320**	**2272**	20316	boulders to clay particles) that has directly
(m^3)	1-2mm	15192	512	9560	injected into river channel.
	0.5 -1mm	12234	412	4780	
	0.25-0.5 mm	10674	360	2390	*'Parabolic segmentation' - Damthiban
	0.125 - 0.25 mm	7398	248	2390	and Rudi groups and 'ArcGIS polygon
	<0.125 mm	21900	740	1195	segment' - LS1 group

** 'Triangular prism' for Damthiban and Rudi groups and 'rectangular segmentation' concept for LS1.

When taken 'triangular prismatic model' for debris flows and 'planar area (ArcGIS polygon) for Ratopahiro and LS1 landslides and the same approach for corresponding groups the total sediment contribution to the river system was found to be 995823 m³ (Table 7-5 depicts total injected and finer values of sediment volume) including fine constituents of **337731** m³.

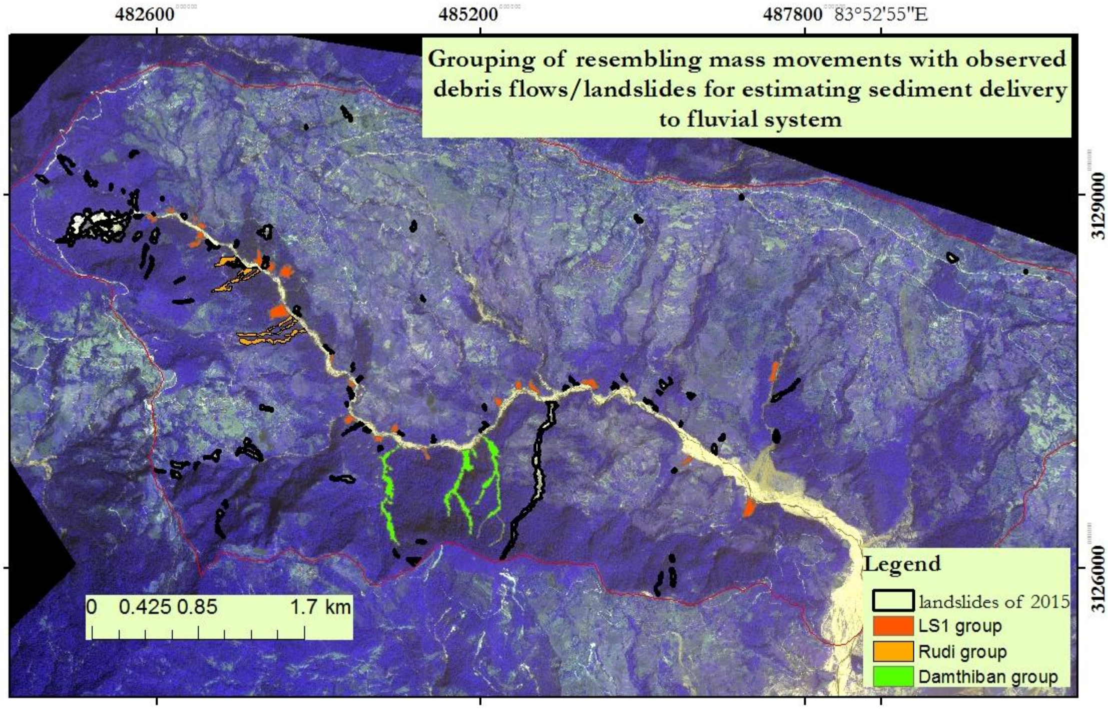


Figure 7-5: Landslides grouping for approximation of direct sediment delivery into the river system.

Total volume obtained by erosional process as discussed earlier (see Figure 7-3) is the volume of fine sediments at the outlet point of Andherikhola basin. The fine constituent calculated from sudden injected volume of landslides is, on the other hand, the sediment at the junction of debris flows/landslides to the river. The sediments by this process reached to the mouth of the river valley was assumed equivalent to the calculated volume taking the findings of Fort and Cossart (2013). They reported a range of sediment that can be transported by the river discharge during and just after the monsoon (i.e. 30 to 60% of total intruded amount) in a research of sub watershed of Kali Gandaki River basin located lesser Himalaya, western Nepal (i.e. Ghattekhola: east to west elongated, 7.8 km²).

Table 7-5: Final sediment volume that added to the Andherikhola river system including original state and finer component (results of 'triangular prism' for debris flows and planar area for landslides). All values are in m³.

	Thulachaur debris flow	Ratopahiro landslide	Damthiban group	Rudi group	LS1 group	Whole basin
Total injected	**131424**	606978	**197301**	**6660**	53460	995825
<2mm	**42984**	206979	**67320**	**2272**	18176	337731
Percent	32.71	34.10	34.12	34.11	34.00	33.91

The fine component volume is 7 times higher to base year erosional sediment yield and 9 times to the year 2015. However, the sediments on the river valley by Ratopahiro is still heaped up. This study did not measured how much volume was washed off by the Andherikhola at its source region. It brings the risk of over prediction in case of Ratopahiro and of total amount to some extent. Plus considering overall error associated with this estimation the direct added volume to the river system was estimated between 871858 and 1119792 m³.

8. CONCLUSION

In this research, the sediment yield for Andherikhola basin by the Revised Morgan Morgan Finney –Daily erosion model that was applied in the PCRASTER GIS platform has shown close agreement with past studies in the area and also in catchments of similar environmental settings. The ancillary datasets and data generated by field and laboratory analysis were inputs where quality of data might have brought some degree of uncertainty to the ultimate results of the sediment flux. The estimated volume of recent debris from landslides (mostly debris flows) to the river system was found to be considerable both in finer constituents and coarse material. This estimation completely relied on field observation data. The answers for initially designed research questions are briefly described as follows:

1. *Which elements of the RMMF erosion model have to be adapted to the Himalayan Environment?*

By the examination of key products and their sensitivity to major soil as well as vegetation parameters, and model performance exercises after the adjustment, this research has come up with following adaptive measures to the RMMF–D erosion model so that the reliable prediction of soil loss in Himalayan catchment can achieve:

(1) The resistance against erosive rain and runoff energy varies for sand, silt and clay. Thus this research incorporates separate equations of detachment and transportation capacity for different particle class of the soil,

(2) The role that saturated hydraulic conductivity plays to reduce runoff during storms by enhancing infiltration rate need to be recognised, this has been done by introducing an initial infiltration base followed by the calculation of runoff as a fraction of rainfall in this research,

(3) The observed high value of saturated hydraulic conductivity, porosity and soil organic matter has provided a fundamental clue that the storage capacity of top soil layer has to be increased above the literature values. Thus incremental effective hydrologic depth from 0.1 to 0.35 m is a proposal for middle mountain Nepalese Himalayan catchments,

(4) Giving due importance to traditional practice of hillslope cultivation which includes well-maintained terraces and bunds on each terrace especially in paddy fields. This practice not only reduces the slope but also enhances storage capacity of storm water which was tested during model performance exercise and found one of the major component to be adjusted in RMMF-D model,

(5) Soils in Middle Mountain regions of the Himalaya have a considerable proportion of gravel which was also obtained in this study, demand the inclusion of stoniness in erosion modelling. This is an additional adjustment this research has made,

(6) daily NDVI map series are of great importance to extract the cover information which influence the rate of interception, evapotranspiration and reduce kinetic energy of rain by creating a barrier to high energy laden raindrops hitting earth surface. The uncertainty associated with these map series because of cloudiness need to be reduced. This research has applied two approaches: (a) ignore images with high cloud cover and (b) threshold for growing season NDVI values.

2. *What is the spatial extent for the distribution of sediment deposits within the catchment in normal years?*

The depositional hotspots were identified mainly in gentle slope terrain units in south facing hills and forested land units in north facing slopes. The role of terraced hillslope most importantly paddy cultivation areas have domination in trapping sediment that removed from upslope. If intervention planned these are the spatial units where conservation efforts can be implemented. Thus a large proportion of sediment from upslope is captured in lower slope units and never reaches the river.

3. *What is the soil loss from the catchment in years without debris flows?*

The base year, for which 2014 is used soil loss from the basin was estimated at 51013 tons with an average rate of 16 tons/ha/y. Settlement clusters, upland rainfed cultivation and pasture have dominant role for this sediment yield.

4. *What is the extent of debris flow runout path that has reached to the river network?*

In a watershed of 27 (26.60) km^2, 0.02 percent area that has mass movements, out of which 79 percent runouts reaching to the river system the same day they were triggered.

5. *What is the volume of earth materials that was initially released?*

Out of total deposited amount, the earth materials that have released initially from the failure zone were varied between 37 % for long debris flows and almost 100 % for small slides. This volume has shown strong positive correlation (i.e. above 0.91 up to 0.99) with the entrained volume and deposits (i.e. separately to total deposits, end deposits and intruded deposits into the river channel).

6. *What is the volume of debris that has injected to the river?*

The direct injection of debris volume from debris flows as well as big and small other types of landslides to main channel of Andheri River was estimated between 871858 and 1119792 m^3. This volume includes wide range of particle sizes, from clay to big boulders the amount of fine sediment (< 2mm) is estimated at 337731 m^3.

7. *What is the incremental erosion rate in 2015 compared to the normal sedimentation rate of the year 2014?*

In the year 2015 the total soil loss from the whole watershed was estimated at 66383 tons (average 17 tons/ha/y) and which is 30% higher in comparison with soil loss in 2014.

8. *What is the net additional sediment from landslides to the fluvial system?*

Net contribution of sediment i.e. finer constituents of direct volume from debris flows which can be transported to downstream plus incremental contribution to sediment flux via erosional processes in 2015 (i.e. 751) was 338482m^3 (337731 +751) at the outlet point of the Andheri River basin.

Advice for future

Taking consideration to the wide application of RMMF erosion model which has also been applied in catchment scale erosion studies, the inclusion of channel erosion for better performance is suggested.

In mountainous soils especially in forested hills the top soil layer has completely differ values of soil attributes. And its role to prevent soil loss is rigorous compared to soil underneath. Thus, to enhance the performance of sensitive parameter such as saturated hydraulic conductivity, and equally to control possible uncertainty that can arise if applied either top soil or subsoil values as inputs in modelling exercises. Interaction of soil vertical layers to water flowing downwards can help better prediction of sediment yields.

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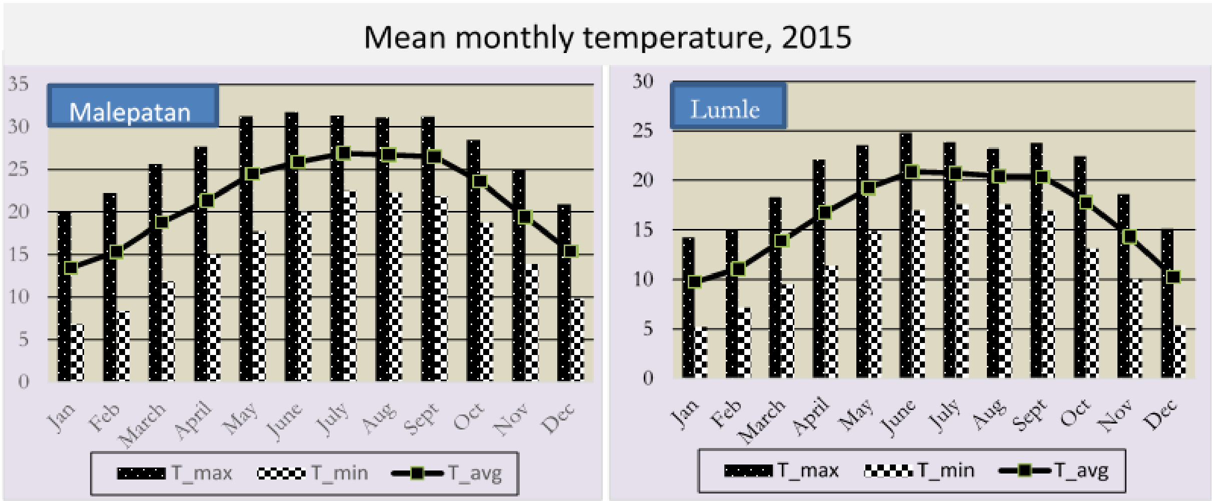
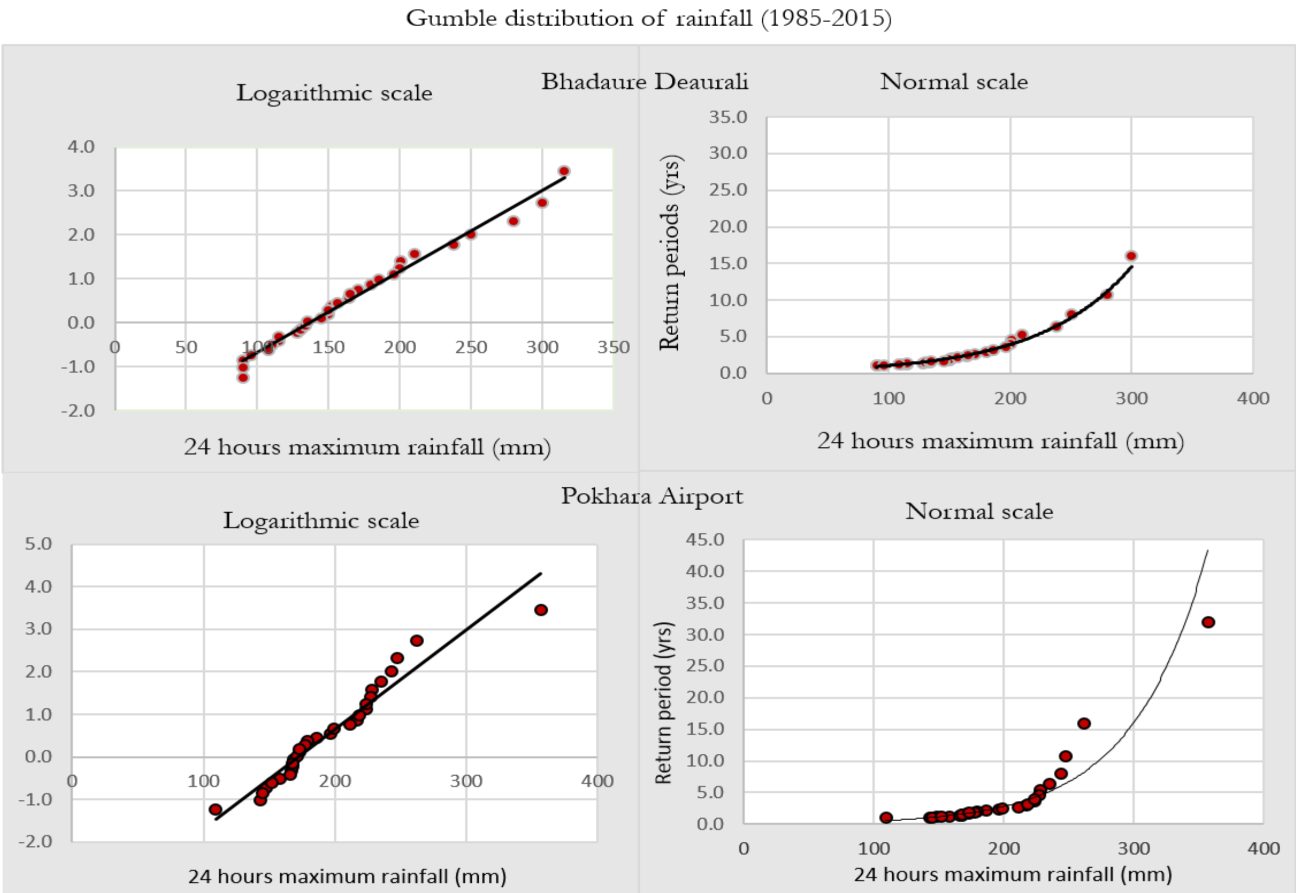
APPENDIXES

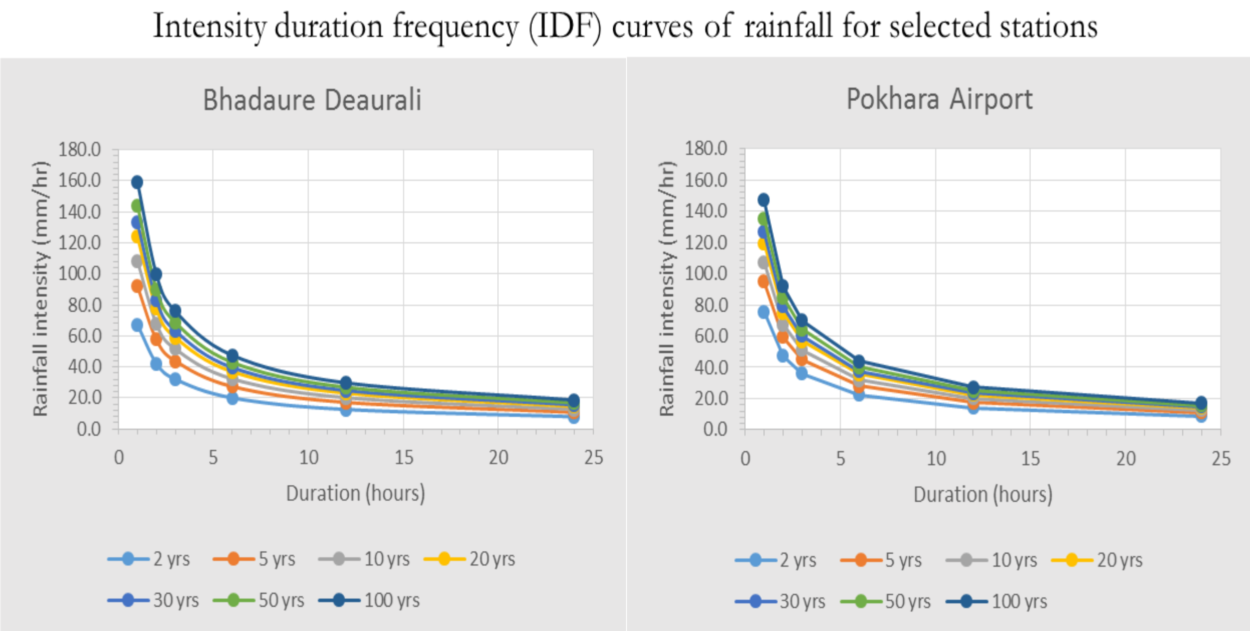
Appendix 1: Mean Monthly temperature of two meteorological stations considered in this research.



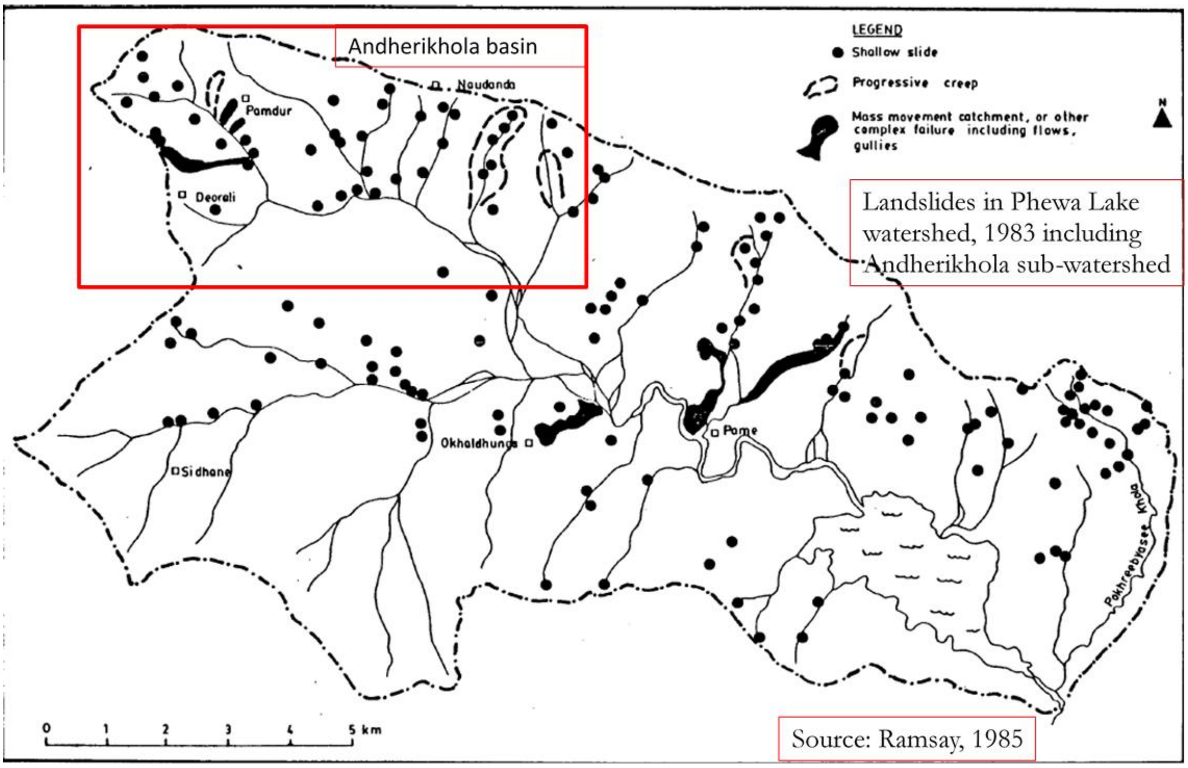
Appendix 2: Gumble distribution of 24 hrs maximum rainfall of precipitation stations taken in this study.



Appendix 3: Intensity duration frequency (IDF) curves of rainfall data of precipitation stations considered.



Appendix 4: Landslide map of Phewa Lake watershed including Andherikhola in the NW (Ramsay, 1985)

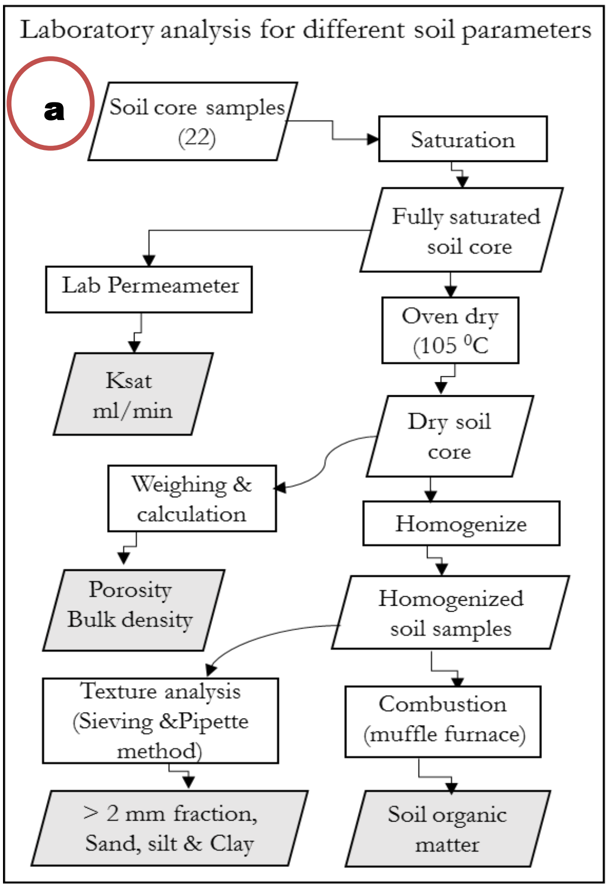


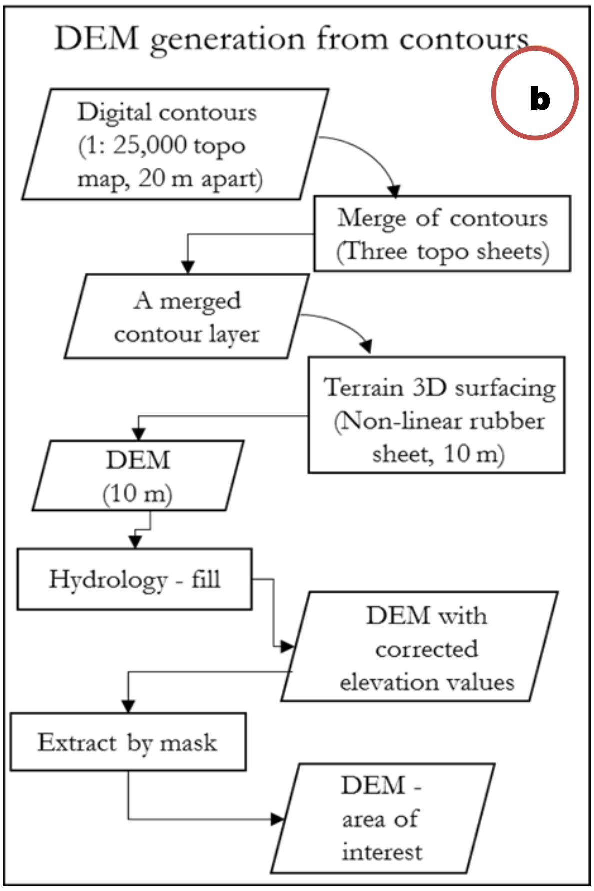
Appendix 5: Key informants including focal persons of different organizations and locals from different villages within Andherikhola watershed.

	Name	Designation	Office/Village
1	Mohan …..	Senior Engineer	Pokhara metropolis
2	Bishnu Prasad Pokhrel	Conservation officer	District Soil Conservation Office, Kaski
3	Krishna Acharya	Engineer	District Development Committee, Kaski
4	Khem Raj Timalsina		Phewa Conservation Office, Pokhara
5	Krishna Prasad Bhandari	Researcher	Tribhuvan University- Institute of Engineering, Pokhara
6	Punya Bhandari	NGO/local	Nagdanda
7	Dil Bahadur Bhattarai	Director	Machhapuchre Development Organization, Pokhara
8	Govinda Pahari	Tourism Entrepreneur	Lakeside Pokhara
9	Sunita Adhakri	Local student	Adhikaridanda
10	Tanka Prasad bhandari	Principal	Laxmi Primary School, Mastok
11	Punya Paudel	Politician	Paudur
12	Lami paudel	Local	Mastok
13	Chudamani paudel	local	Laxmi Deurali
14	Bhesh Raj Paudel	Local	Prebasti
15	Aaita Bahadur Kami	Local	Kaule
16	…. Sarki	Local	Reeedanda
17	Tarapati Dahal	Victim/local	Paundi
18	Manohari Dahal	Local	Paundi
19	Govinda Paudel	local	Paudurghumti
20	Yuwaraj Bhandari (Sashi)	Local student	Nagdanda

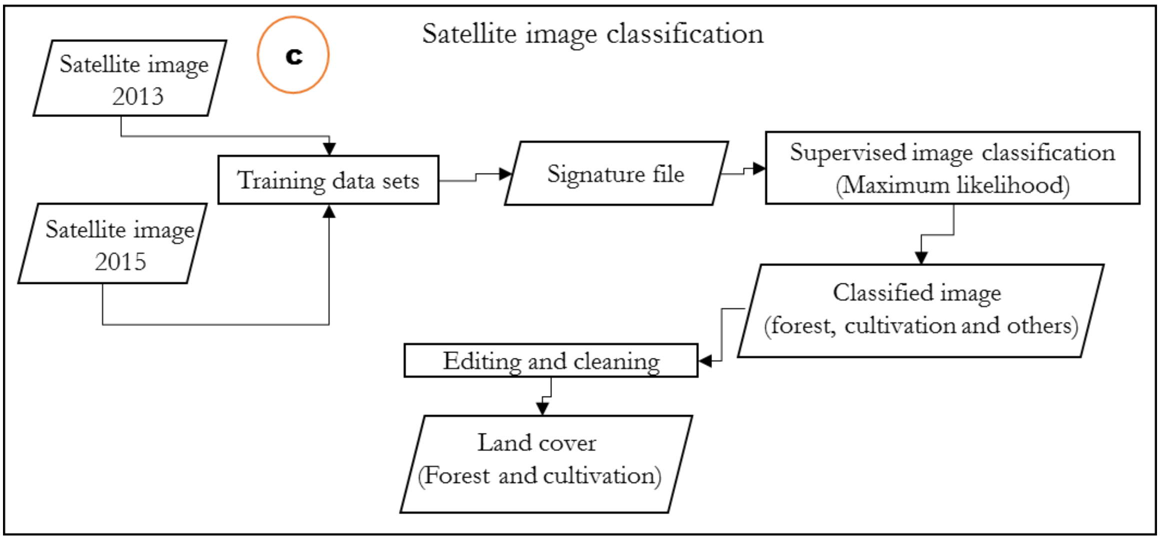
Appendix 6:

A: Laboratory analysis of soil parameters; B: DEM generation from Contours

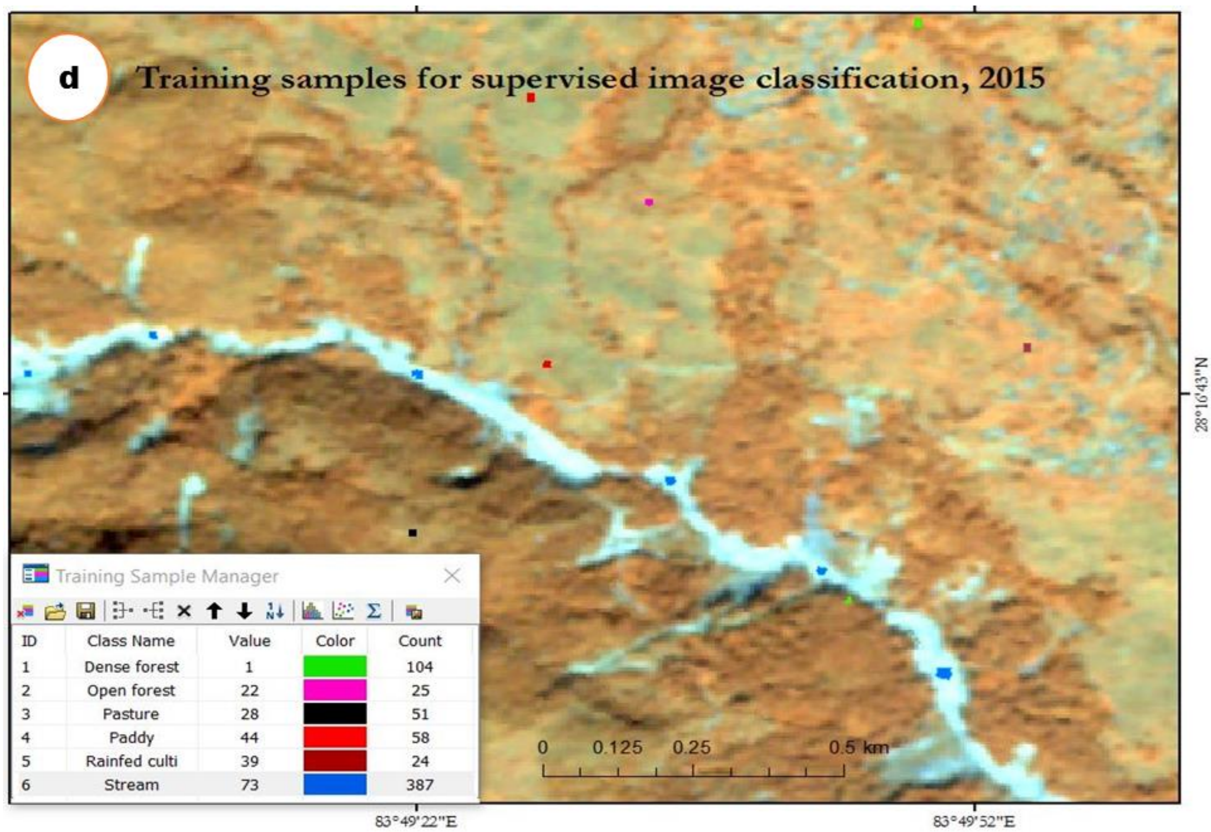




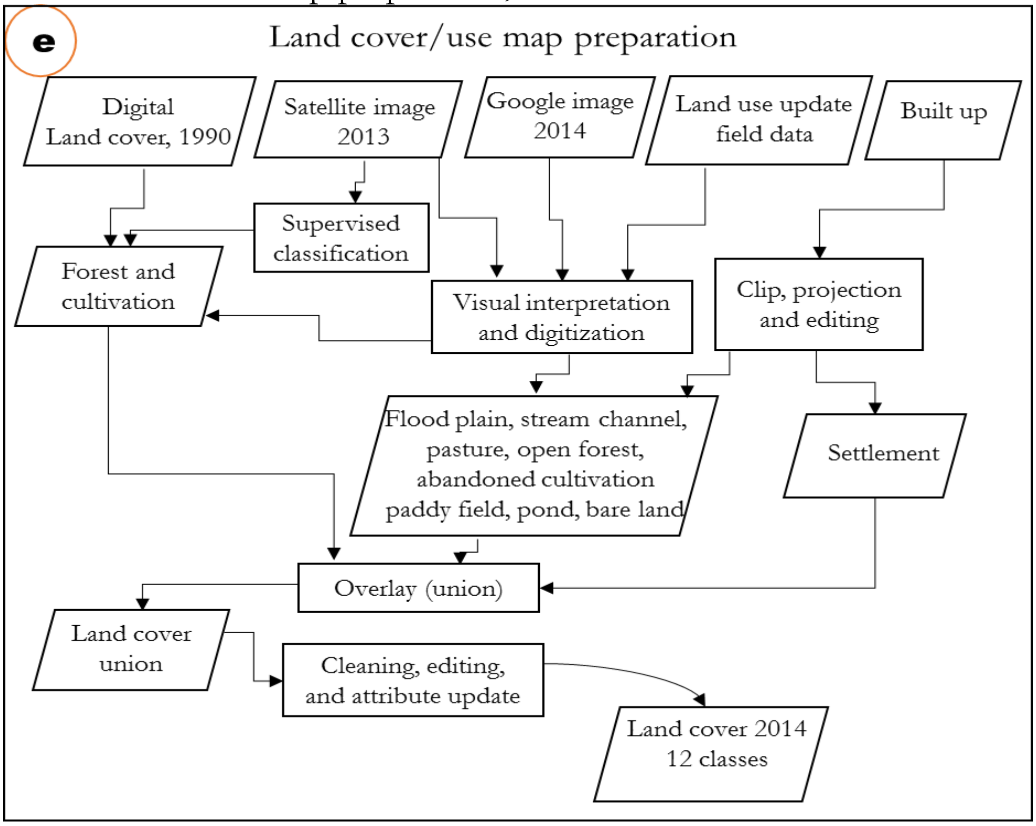
C: Satellite image classification



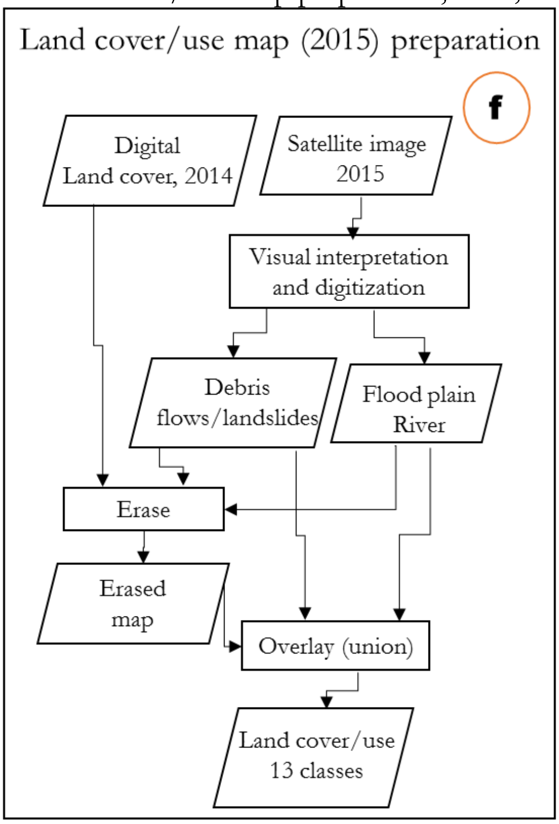
D: Training samples for supervised image classifications, 2015



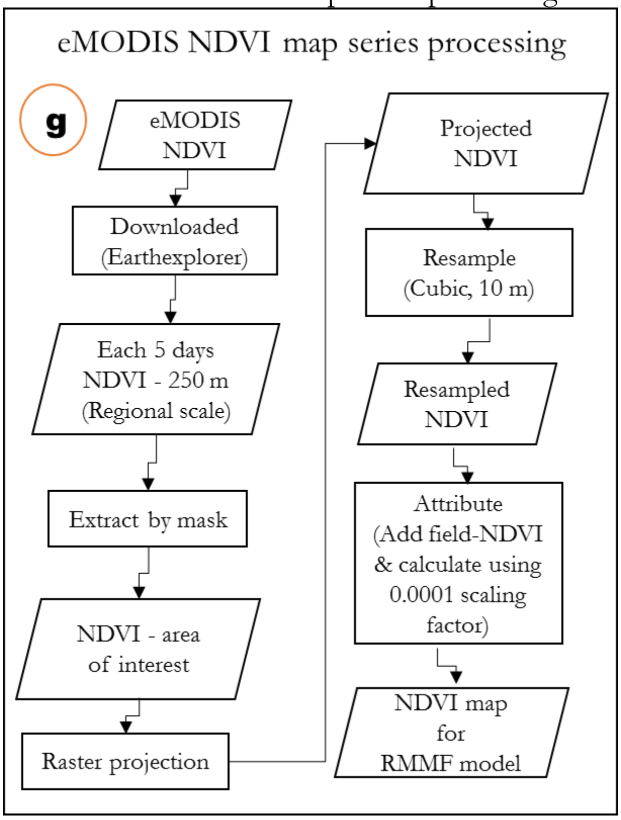
E: Lad cover/use map preparation, 2014



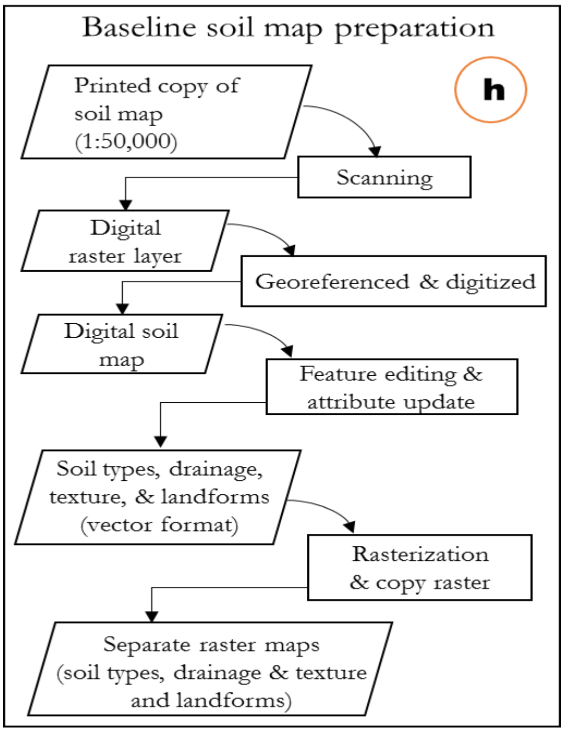
F: Land cover/use map preparation, 2015;



G: eMODIS NDVI map series processing



H: Baseline soil map preparation from land system map acquired from GoN.



Appendix 7: Land cover/use classes in 2014 and 2015 with area coverage.

Land	**Area_ha_2015**	**Area_ha_2014**
Dense forest	725.38	774.46
Open forest	170.76	176.29
Paddy field	669.00	697.69
Rainfed	593.76	600.27
Pasture	59.40	59.80
Abandoned	16.72	17.23
Settlement	277.76	277.90
River	84.38	53.50
River water	11.20	3.46
Debris flows	23.37	
Landslides	30.60	2.81
Pond	0.20	0.20
	2662.53	2663.62

Appendix 8: NDVI values of all maps (downloaded) which were used to correct cloud effects.

				NDVI_2014			NDVI_2015		
SN	Month	Days	DOY	Min	Max	Mean	Min	Max	Mean
1	Jan	1	1	0.411	0.859	0.637	0.060	0.888	0.507
2		6	6	0.385	0.833	0.606	0.339	0.823	0.607
3		11	11	0.409	0.840	0.624	0.467	0.828	0.649
4		16	16	0.453	0.845	0.649	0.485	0.821	0.653
5		21	21	0.434	0.806	0.624	0.478	0.818	0.648
6		26	26	0.441	0.806	0.623	0.493	0.852	0.674
7	Feb	1	32	0.447	0.820	0.633	0.475	0.975	0.665
8		6	37	0.434	0.841	0.637	0.340	0.975	0.637
9		11	42	0.357	0.841	0.618	0.493	0.851	0.666
10		16	47	0.426	0.895	0.634	0.034	0.924	0.482
11		21	52	0.419	0.810	0.616	0.174	0.815	0.518
12		26	57	0.430	0.854	0.641	0.034	0.924	0.482
13	March	1	60	0.436	0.853	0.645	0.466	0.920	0.667
14		6	65	0.431	0.798	0.612	0.466	0.818	0.645
15		11	70	0.447	0.816	0.631	0.426	0.782	0.609
16		16	75	0.421	0.821	0.620	0.472	0.818	0.648
17		21	80	0.446	0.821	0.634	0.458	0.834	0.639
18		26	85	0.420	0.775	0.597	0.080	0.887	0.498
19	Apr	1	91	0.372	0.781	0.577	0.415	0.892	0.653
20		6	96	0.429	0.827	0.628	0.419	0.842	0.632

21		11	101	0.343	0.799	0.570	0.063	0.881	0.502
22		16	106	0.384	0.796	0.590	0.463	0.878	0.669
23		21	111	0.449	0.864	0.640	0.400	0.769	0.584
24		26	116	0.222	0.907	0.596	0.477	0.961	0.702
25	May	1	121	0.372	0.905	0.625	0.477	0.960	0.701
26		6	126	0.372	0.905	0.625	0.447	0.877	0.662
27		11	131	0.441	0.870	0.648	0.450	0.876	0.664
28		16	136	0.441	0.899	0.670	0.462	0.854	0.657
29		21	141	0.392	0.930	0.644	0.512	0.896	0.704
30		26	146	0.393	0.928	0.677	0.538	0.893	0.717
31	Jun	1	152	0.058	0.845	0.500	0.535	0.876	0.702
32		6	157	0.243	0.857	3079.09	0.438	0.860	0.655
33		11	162	0.243	0.857	0.573	-0.029	0.863	0.423
34		16	167	0.000	0.866	0.441	-0.021	0.941	0.465
35		21	172	0.054	0.865	0.462	0.358	0.938	0.500
36		26	177	-0.040	0.867	0.417	-0.223	0.949	0.424
37	July	1	182	-0.041	0.949	0.458	-0.041	0.949	0.458
38		6	187	0.050	0.844	0.449	0.050	0.844	0.449
39		11	192				-0.002	0.955	0.484
41		21	202	-0.302	0.989	0.336	0.207	0.953	0.492
42		26	207	-0.036	0.913	0.447	0.021	0.953	0.492
43	Aug	1	213				0.062	0.902	0.494
44		6	218				0.062	0.902	0.494
45		11	223				-0.239	0.993	0.391
46		16	228	-0.238	0.892	0.361	0.016	0.993	0.486
47		21	233	0.441	0.902	0.499	-0.035	0.907	0.442
48		26	238	-0.262	0.896	0.425	0.036	0.908	0.471
49	Sept	1	244	0.055	0.906	0.483	0.036	0.908	0.471
50		6	249	0.043	0.958	0.514	0.061	0.959	0.519
51		11	254	0.080	0.964	0.552	0.061	0.959	0.519
52		16	259	0.091	0.966	0.442	0.006	1.005	0.525
53		21	264	0.053	0.986	0.508	-0.018	0.934	0.465
54		26	269	0.001	0.953	0.495	0.058	0.961	0.517
55	Oct	1	274	0.619	0.961	0.807	0.058	0.961	0.517
56		6	279	0.670	0.987	0.836	0.402	0.937	0.706
57		11	284	0.540	0.949	0.770	0.019	0.898	0.557
58		16	289	0.327	1.003	0.671	0.071	0.887	0.483
59		21	294	0.120	1.022	0.661	0.076	0.883	0.558
60		26	299	0.020	0.882	0.477	0.409	0.875	0.654
61	Nov	1	305	0.183	0.891	0.546	0.113	0.879	0.588
62		6	310	0.049	0.963	0.556	0.388	0.925	0.672
63		11	315	0.070	0.931	0.484	0.388	0.925	0.681
64		16	320	0.061	0.836	0.462	0.402	0.922	0.676
65		21	325	0.242	0.928	0.594	0.136	0.923	0.544
66		26	330	0.439	0.928	0.684	-0.003	0.853	0.429
67	DEC	1	335	0.454	0.931	0.685	0.333	0.811	0.574
68		6	340	0.360	0.835	0.617	0.351	0.870	0.624
69		11	345	0.445	0.845	0.654	0.399	0.876	0.643
70		16	350	0.490	0.814	0.655	0.301	0.842	0.593
71		21	355	0.453	0.870	0.668	0.320	0.845	0.614
72		26	360	0.364	0.870	0.646	0.364	0.870	0.646

Appendix 9: Values of soil parameters including cohesion, porosity, bulk density, saturated hydraulic conductivity and organic matter for all samples considered in this research.

Sample	Landuse	Y	X	Z	Cohesion kPa	Porosity % vol.	BD g/cm³	Ksat mm/hr	SOM % wt.
s1	Abandoned cultivation	28.273239	83.867542	1244.015	161.81	58.78	1.04	**685.59**	7.81
s2	Open forest	28.269376	83.860227	1044.211	49.03	50.11	1.05	**1044.71**	4.89
s3	Dense forest	28.27574	83.81476	1806.568	142.20	**71.43**	0.73	93.4	**16.60**
s4	Rangeland	28.289818	83.819283	1794.605	56.88	66.93	1.07	61.40	**16.98**
s5	Paddy field	28.283889	83.821761	1576.693	186.33	63.97	0.99	4.99	11.53
s6	Rainfed cultivation	28.276963	83.83486	1390.563	88.26	55.60	1.18	15.16	7.32
s7	Paddy field	28.274539	83.840595	1279.767	98.07	60.28	1.11	**568.06**	7.71
S8	Pasture	28.28723	83.83561	1628.75		52.25	1.31	0.74	4.81
s9	Open forest	28.284821	83.849096	1498.644	186.33	62.43	0.95	15.21	7.82
s10	Rainfed cultivation	28.281122	83.862527	1413.525	83.36	56.81	1.15	8.62	7.74
s11	Paddy field	28.27861	83.876527	1402.61	68.65	63.16	1.06	9.28	6.06
s12	Dense forest	28.254322	83.879823	850.94	107.87	66.63	0.57	**682.92**	12.14
s13	Open forest	28.26229	83.878797	1111.838	63.74	40.64	1.15	168.35	2.07
s14	Abandoned cultivation	28.27269	83.82357	1619.609	147.10	62.83	0.96	1.86	14.62
s15	Paddy field	28.261052	83.835719	1333.213	186.33	65.79	0.98	0.00	11.22
s16	Rainfed cultivation	28.264548	83.830242	1382.168	59.82	61.45	0.89	11.82	9.71
s17	Dense forest	28.273511	83.830393	1410.231	68.65	**72.09**	0.63	**555.59**	**16.96**
s18	Open forest	28.267636	83.851413	987.868	68.65	42.07	0.92	58.51	2.52
s19	Dense forest	28.25559	83.848242	1403.603	44.13	**75.92**	0.50	182.82	**18.78**
s20	Dense forest	28.262654	83.844198	1050.5	53.94	55.72	1.23	12.03	8.13
s21	Rainfed cultivation	28.26068	83.85779	1100.56	147.10	60.89	1.07	2.55	11.14
s22	Rainfed cultivation	28.257652	83.866518	932.17	70.61	58.95	1.12	0.28	12.49
s23	Paddy field	28.283881	83.821697		196.13				
s24	Forest	28.280557	83.818399		107.87				
s25	Pasture landslide	28.285655	83.837091		98.07				
s26	Khet landslide	28.278709	83.829682		83.36				
s27	Landslide	28.278675	83.823934		63.74				
s28	Pasture landslide	28.285521	83.837872		157.89				
s29	Bari landslide	28.278912	83.872638		63.74				
s30	Bari landslide	28.27845	83.87446		49.03				
s31	Khet landslide	28.278484	83.876264		147.10				
s32	Pasture landslide	28.279227	83.876539		88.26				
	Minimum				44.13	40.64	0.50	0.00	2.07
	Maximum				196.13	75.92	1.31	1044.71	18.78
	Average				103.03	60.22	0.98	190.17	9.96
	Standard deviation (SD)				48.15	8.73	0.21	304.11	4.75
	Coefficient of variance (CV) %				46.73	14.50	21.41	159.90	47.67

Appendix 10: Percentage of coarse fraction and fine particles of soil and soil texture classes for all samples including 'duplicating' and 'reference' sample that obtained from soil texture analysis.

Sample	Percentage of course fraction & fine soil particles												
	> 2mm	Sand	Sand	Sand	Sand	Sand	SAND	Silt	Silt	SILT	Clay		
Ref., Nepal		0.09	0.31	1.79	14.46	8.39	25.04	25.76	28.31	54.07	16.22	Silty loam	Min, max, average, SD, & CV calculation has excluded reference sample and duplicate (s6-d & s20-d) samples.
s6-d	3.88	5.14	3.51	5.78	22.32	11.03	47.79	11.76	17.01	28.77	12.24	Loam	
s20-d	0.00	12.87	7.81	7.19	19.02	11.44	**58.34**	11.25	16.57	27.82	5.71	Sandy loam	
s1	12.29	3.14	3.32	3.02	7.25	7.88	24.61	9.67	27.54	37.21	18.09	Silty loam	
s2	7.89	9.75	7.40	5.63	11.24	11.54	45.55	12.47	23.58	36.05	5.61	Sandy loam	
s3	0.00	1.06	1.09	3.01	23.85	14.35	43.37	8.80	16.90	25.70	14.34	Loam	
s4	0.00	3.00	0.85	0.94	3.70	5.50	13.99	9.61	32.97	42.58	26.45	Silty loam	
s5	2.37	2.13	1.04	0.91	2.27	2.76	9.12	10.47	37.33	47.80	**29.18**	Silty clay loam	
s6	3.88	9.37	3.57	5.47	21.62	11.16	**51.20**	10.89	16.54	27.43	10.18	Loam	
s7	5.44	7.26	1.42	1.41	5.98	8.81	24.87	17.62	29.89	47.51	14.46	Silty loam	
s8	6.78	9.42	7.51	5.54	9.49	10.81	42.77	15.88	21.66	37.54	8.09	Loam	
s9	10.35	12.87	3.50	2.85	8.65	10.87	38.75	18.14	19.76	37.89	5.19	Silty loam	
s10	11.90	8.80	4.54	3.12	6.11	8.34	30.91	11.23	24.50	35.73	13.72	Silty loam	
s11	0.00	3.78	5.29	4.51	7.58	9.26	30.42	21.21	33.77	**54.98**	8.54	Silty loam	
s12	6.68	5.09	4.96	4.50	5.58	4.93	25.06	16.20	25.07	41.27	14.86	Silty loam	
s13	**39.99**	10.47	5.63	4.07	8.46	8.55	37.19	6.69	11.36	18.05	2.70	Silty loam	
s14	0.00	1.82	1.09	1.30	4.67	4.25	13.13	9.17	31.02	40.19	**32.06**	Silty Clay loam	
s15	0.00	0.59	1.12	1.25	6.64	9.84	19.44	14.62	34.64	49.27	20.07	Silty loam	
s16	13.49	5.26	1.28	0.90	0.54	10.69	18.67	17.78	28.07	45.85	12.28	Silty loam	
s17	0.00	2.63	1.96	4.62	16.13	6.75	32.09	7.23	24.91	32.15	18.80	loam	
s18	**57.70**	4.75	2.50	2.18	5.35	5.09	19.87	4.92	13.25	18.17	1.74	Silty loam	
s19	6.33	3.68	0.31	3.61	15.94	8.52	32.05	9.16	17.50	26.66	16.19	Silty loam	
s20	0.00	11.71	6.76	7.07	19.72	11.73	**56.99**	12.96	16.77	29.73	5.16	Sandy loam	
s21	2.37	1.59	2.46	2.67	4.00	3.72	14.44	9.62	36.84	46.46	25.59	Silty loam	
s22	0.00	0.56	1.28	1.82	3.55	4.28	11.49	8.89	33.95	42.83	33.19	Silty clay loam	
Minimum	0.00	0.56	0.31	0.90	0.54	2.76	9.12	4.92	11.36	18.05	1.74		
Maximum	57.70	12.87	7.51	7.07	23.85	14.35	56.99	21.21	37.33	54.98	33.19		
Average	**8.52**	**5.40**	**3.13**	**3.20**	**9.02**	**8.17**	**28.91**	**11.96**	**25.36**	**37.32**	**15.29**		
S.D	14.08	3.87	2.28	1.79	6.44	3.13	13.55	4.29	7.88	9.95	9.38		
CV	**165.22**	**71.80**	**72.75**	**56.05**	**71.44**	**38.29**	**46.88**	**35.84**	**31.09**	**26.67**	**61.31**		

Appendix 11: An example table demonstrating the sediment volume estimation carried out in this study taking the case of Damthiban debris flow.

zone	D	W	Area #	L	Volume_1 (Area# * D)				Volume_2 (1/2*D*W*L)				Volume_3 (2/3*D*W*L)				Volume_4 (D*W*L)			
					Tot	**Rel**	**Tran**	**Dep**	**Tot**	**Rel**	**Tran**	**Dep**	**Tot**	**Rel**	**Tran**	**Dep**	**Tot**	**Rel**	**Tran**	**Dep**
Rel.	10	7	1161	178	11609	11609		11609	6381	6381			8508	8508			12763	12763		12763
Rel.	9	11	2611	337	23503	23503		23503	16894	16894			22525	22525			33788	33788		33788
Rel.	8	31	3675	133	29402	29402		29402	16338	16338			21784	21784			32675	32675		32675
Rel.	8	23	3159	140	25272	25272		25272	12622	12622			16830	16830			25245	25245		25245
Tran	7	18	5391	259	37740		37740	7548	16417		16417	16417	21889		21889	21889	32833		32833	6567
Tran	10	36	5255	153	52547		52547	10509	27869		27869	27869	37159		37159	37159	55738		55738	11148
Tran	11	28	3750	108	41247		41247	8249	16442		16442	16442	21923		21923	21923	32884		32884	6577
Dep	11	67	7586	127	83440		on the path	83440	46932			46932	62576			62576	93864			93864
Dep	12	36	3410	103	40916			40916	22421			22421	29895			29895	44842			44842
Release			**10606**			**89785**	**131534**	**240448**		52235	60728	**130081**		69647	80970	**173441**		**89785**	**131534**	**267468**
Transport			**14396**		Entrained	150663	ED	240448		77846		83149		103794		110865		177683		173604
Deposition			**10995**				fan	17381				17381				17381				17381
							IR	223067				65767				93484				156222
							% fine	42				42				42				42
							IR_f	**92952**				**27405**				**38955**				**65098**

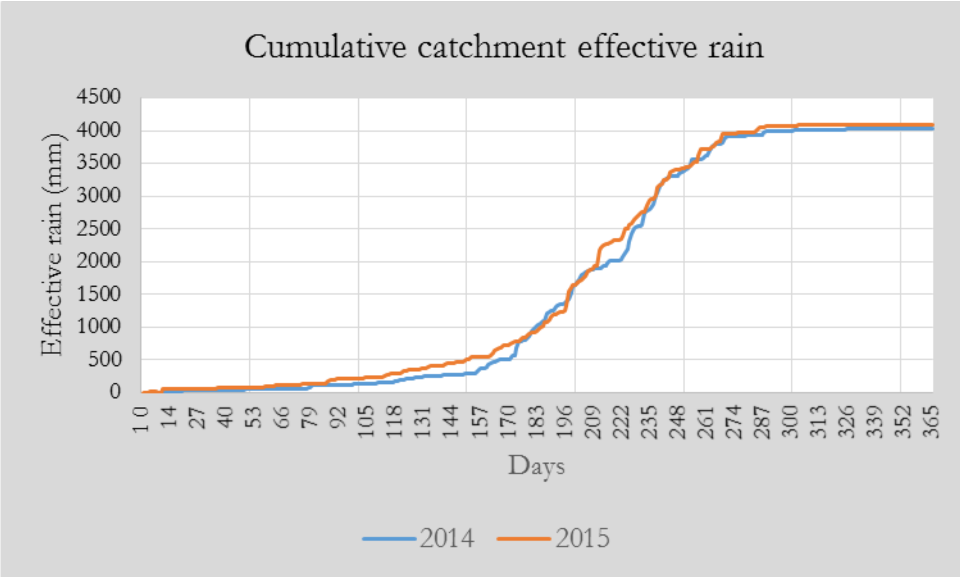
Appendix 12: Comparative summary of morphometric variables and estimated volume according to Ramsay (1985) and the current research. (Measurement units: area-m^2, volume-m^3, width and depth-meter and slope-degree).

	Ramsay (1985)			Current research			
	Paudur, (complex landslide)	Bhadaure Deurali (debris slide)	Kaskikot (shallow slide)	Ratopahiro (landslide)	Damthiban (debris flow)	Thulachaur (debris flow)	DF1 (debris flow)
Scar area	25,200	122,000	750	33,407	10,606	14,898	836
Total area	42,000	132,000	2750	84,271	35,997	51,699	41,96
Length	840	1620	110		1293	1372	172
Max depth	<10	10	2	18	12	17.1	2.1
Max width		134	30	69	67	58	32
Slope	5- 35	18- 30	37	8- 65	4 - 65	1 - 60	2 – 47
Volume	126,000	730,000	975	619,834	240,448	443,184	3,950

Appendix 13: Pearson correlation of initially released earth to entrain and deposits including 'end' (ED), 'total' (TD) and 'intruded into the river' (IR) for all volume estimation approaches.

	Damthiban	Thulachaur	Rudi	DF1	Ratopahiro	LS1	r2
			Vol_1				
R	**89785**	**158635**	**24624**	**1756**	**304659**	**3979**	
E	150663	284552	14906	2194	315174		0.927357
TD	240448	443187	39530	3950	619834		0.978185
ED	157008	378079	1589	3580		3949	0.983506
IR	139626	317037	795		606978	2430	0.996983
			Vol_2				
R	**52235**	**81320**	**13743**	**915**			
E	77846	140156	575	644			0.988312
TD	130081	221476	14317	1559			0.995082
ED	83149	192466	2459	1401			0.973697
IR	**65767**	**131424**	**1665**				0.996208
			Vol_3				
R	**69647**	**108427**	**18324**	**1220**			
E	103794	186875	766	859			0.988311
TD	173441	295302	19090	2079			0.995082
ED	110865	256621	3279	1867			0.973698
IR	**93484**	**195580**	**2485**				0.993581
			Vol_4				
R	**89785**	**162641**	**27486**	**1830**	**338046**	**4080**	
E	177683	277521	6244	239	338212		0.91943
TD	267468	440161	33729	2070	641926	4080	0.968776
ED	173604	382140	4919	1751		4080	0.988505
IR	156222	321099	4124		# 631843	2716	0.991129

Appendix 14: Cumulative effective rain for the year 2014 and 2015 of Andherikhola watershed



Appendix 15: Particle size of sediments for four debris flows and a complex landslide (from >2mm to <0.125 mm). Column 3 i.e. '< 2mm total' is a total value of all five classes of sand from column 4 to 8 (i.e. column 1 + column 2 = 100%, and <2mm = sum of all five finer categories).

Zones	Values in percentage						
	>2mm	< 2mm total	1-2mm	0.5 -1mm	0.25-0.5 mm	0.125 – 0.25 mm	<0.125 mm
Thulachaur debris flow							
Upslope depo	79.31	20.69	3.45	3.45	3.45	3.45	6.9
Initiation	54.55	45.45	9.09	4.55	6.06	13.64	12.12
Initiation	63.83	36.17	4.26	2.13	6.38	4.26	19.15
Fan	77.59	22.41	3.45	2.76	8.62	5.17	1.72
Transport	61.19	38.81	13.43	7.46	7.46	2.99	7.46
Average	67.29	32.706	6.74	4.07	6.39	5.9	9.47
Damthiban debris flow							
Initiation	58.33	41.67	3.33	5	5	1.67	26.67
Initiation	73.58	26.42	5.66	5.66	5.66	3.77	5.66
Transport	67.44	32.56	11.63	6.98	4.65	2.33	6.98
Upslope depo	60	40	10	4	6	4	16
Deposit	61.9	38.1	9.52	9.52	7.14	4.76	7.14
Fan	74	26	6	6	4	6	4
Average	65.87	34.12	7.7	6.2	5.41	3.75	11.1
Ratopahiro complex landslide							
Initiation	52.36	47.64	13.09	7.85	2.62	15.71	8.38
Initiation	63.64	36.36	9.09	4.55	4.55	13.64	4.55
Initiation	65	35	1	10	15	5	4
Initiation	82.61	17.39	4.35	2.61	8.7	0.87	0.87
Average	65.9	34.1	6.88	6.25	7.72	8.8	4.45
DF1 debris flow							
Upslope depo	66	34	16	8	4	4	2