J. Mt. Sci. (2008) 5: 38–51
DOI 10.1007/s11629-008-0038-7

Spatial Variability of Mass Movements in the Satluj Valley, Himachal Pradesh during 1990 ~ 2006

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Abstract: Satluj Valley is known to have a history of landslides and related mass movement activities since the geological times. Geological and geomorphological settings combined with anthropogenic activities constitute a propensity towards slope failure. During the last two decades, the area witnessed substantial increase in athropogenic pressure, mainly due to the exploitation of hydropower potential, changing landuse pattern and population growth. In addition, a shift of the climatic patterns in the form of larger area falling under the influence of rains was observed. These natural as well as anthropogenic changes in the area have resulted in increased spatial coverage of landslide in the area. This paper documents these changes during 1990 ~ 2006.

Keywords: Landslides; Mass movement; Satluj Valley; Himachal Pradesh; India

Introduction

Landslides and related mass movement phenomena are the major causes of the loss of life, injury and damage to property in the Himalayan region. A reliable landslide inventory defining the types and activities of all landslides as well as their spatial distribution is essential before any analysis of occurrences of landslides and their relationship to environmental conditions are undertaken. However, these landslide inventories are not yet very common and are available only for a limited area.

In the early 1990s, a research project on landslide hazard zonation was started in the Satluj Valley, Himachal Pradesh. The goal of the project was to map the type and distribution of landslides at regional scale, and to assess various landslide hazard susceptible zones. Investigation was carried out at different scales and confirmed that mass movements were widespread in the region (BARTARYA et al. 1996, SAH et al. 1996, VIRDI et al. 1995, GUPTA 1998). Steep slopes, high relief, a number of structural discontinuities and underlying geology combined with anthropogenic activities constituted a propensity towards failure. An inventory of active landslides was prepared using extensive field mapping (GUPTA et al. 1993).

Since 1990s, the Satluj Valley had witnessed an increase in development activities mainly because of the construction of many hydropower projects. Number of cloud bursts along with two major flash flood events due to breaching of landslide generated lakes in the Tibetan Plateau during 2000 and 2005 has also been reported in the valley (GUPTA and SAH 2007). The geomorphological hazard mapping in the area also documents number of landslide events in the past. The spatial location of these paleolandslides is shown by Figure 1a. The area was revisited and mapped again in 2003, 2004, 2005 and 2006 to assess the spatial distribution of active mass movements (Figure 1b). This paper highlights the changes in the spatial variability of mass movements during 1990 ~ 2006.

Received: 31 July 2007
Accepted: 26 September 2007

1 Study Area

1.1 Location

The study area falls between longitudes 77°57′ ~ 78°40′E and latitudes 31°25′ ~ 31°50′N encompassing a stretch of about 130 km between Nathpa and Malling villages in Kinnaur District of Himachal Pradesh (Figure 1a). The Satluj River originating from the Mansarovar Lake, at an elevation of about 5640 m, is the major channel flowing through the area. It enters India at Shipki La at an elevation of 3048 m, through a deep and narrow gorge. A national highway (NH-22), which is the main lifeline of the people living in the area, follows the Satluj River about 20 ~ 100 m above the river. The old and abandoned road also traverses the area at a height of about 500 m from the Satluj River. Many tributaries join the Satluj River on its two sides. The Spiti and Baspa are the major rivers meeting the Satluj River at Khab and Karchham, respectively. The other tributaries joining the Satluj River from upstream to downstream are Titang Khad, Ropa Gad, Tangla Khad, Taiti Garang, Tirung Khad, Roldang Nala, Kashang Khad, Dumti Khad, Tangling Khad, Raura Gad, Duling Khad, Melan Khad, Panwi Khad and Wanger Khad, (Figure 1a & b).

1.2 Geomorphological and geological set up

The present landscape of the area has been carved by the Satluj River and its tributaries. Geomorphologically, the entire area depicts a highly rugged and unstable topography due to its high relief and active erosion processes. The relief along the valley slope varies between 1000 m and 4000 m. Two major peaks, the Leo Pargil (6790 m) in the northeast and the Kinner Kailsh (6050 m) in the south surround the area. Amongst the geomorphic processes, glacial and fluvial processes have played a dominant role in the terrain evolution in the past. Most of the processes currently operating in the area are denudational, but depositional processes also occur.

The slopes in the area are generally steep, with angles greater than 40°. These mainly consist of barren rocks covered with scattered trees and bushes, however, at places, 5 ~ 10 m thick glacial and periglacial deposits are observed. In the lower reaches, the valley is 'V' shaped and terminates into a narrow gorge along the Satluj River. The gorge section is nearly vertical to subvertical and is about 200 ~ 300 m deep. Fluvial terraces, debris fans and talus cones are other geomorphic features present along the valley slopes. In the upper reaches, the glaciers and snow-capped peaks are the prominent features.

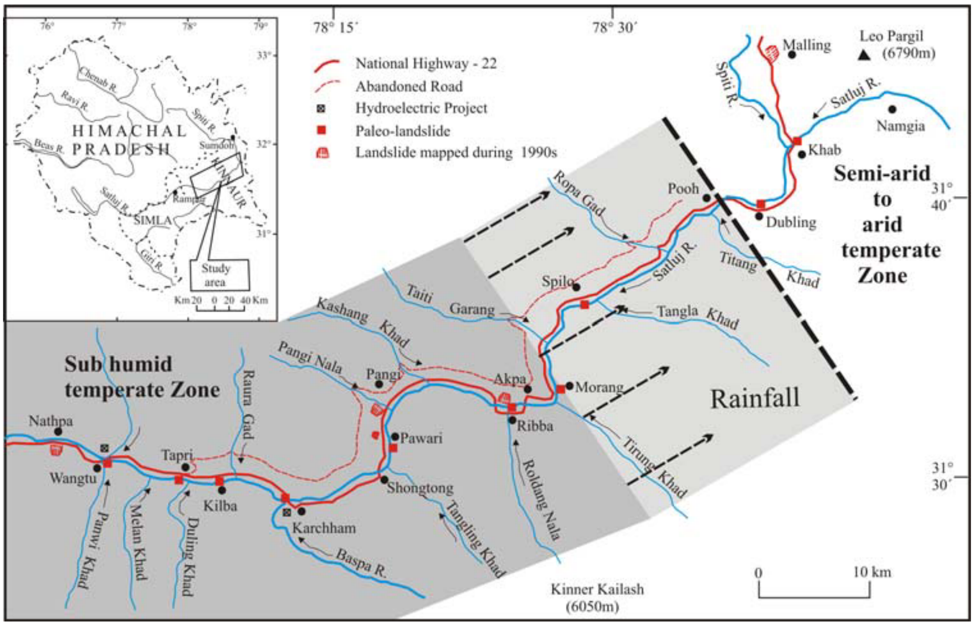

Figure 1a Location map of the area depicting paleolandslides as well as spatial distribution of the landslides mapped during 1990s. The northeastward penetration of the sub-humid temperate zone is marked.

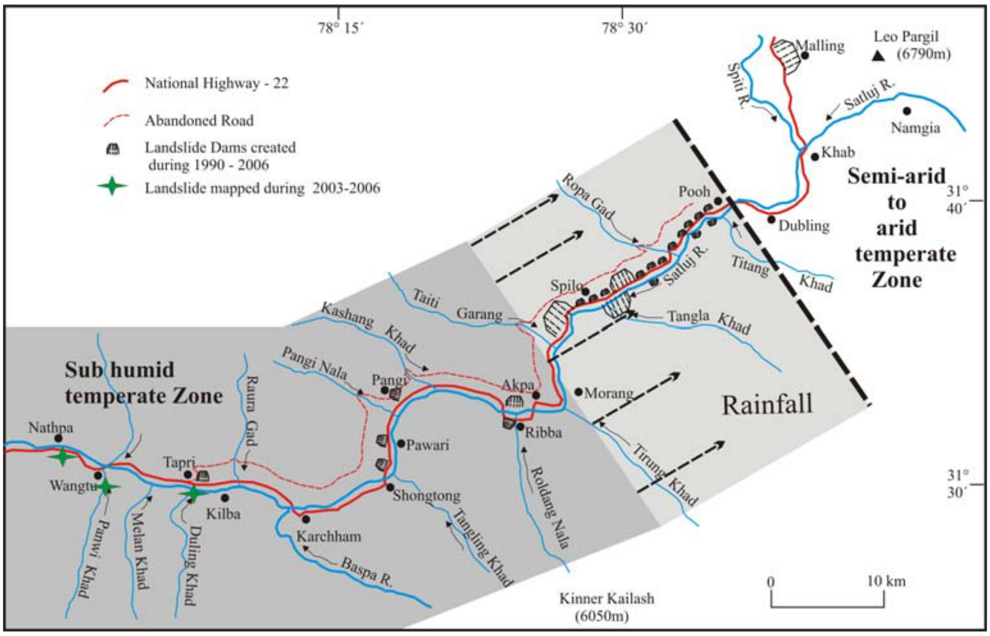

Figure 1b Map showing spatial distribution of the landslides mapped in 2003, 2004, 2005 and 2006. Landslide dams created during 1990 ~ 2006 are marked.

Geologically, the study area cuts across the entire Higher Himalayan sequence, and is made up of a thick succession of medium to high-grade metasediments belonging to the Wangtu Gneissic Complex, the Vaikrita Group and the Haimanta Group, and their sedimentary cover of the Tethyan sequence. Near Akpa and Leo Pargil, these have been intruded by early Paleozoic and Tertiary leuco-granites, respectively. The geological setting of this part of the valley has been studied in detail by SHARMA (1976), SHARMA (1977), TEWARI et al. (1978), BASSI and CHOPRA (1983), KAKKAR (1988) and GUPTA (1998). Apart from having a wide variation in lithology, the river valley has an extensive cover of glacial, glacio-fluvial, fluvial and paleo-slided material of Quaternary origin. These have been mapped earlier by GUPTA et al. (1993).

1.3 Climate

Climatically, the study area lies in the “rain shadow” zone. Based on the amount of annual precipitation and the variation in temperature, the area has been divided into two broad climatic zones; (i) Sub-humid temperate zone extending between Nathpa and Morang; and (ii) Semi-arid to arid temperate zone (Cold desert) extending from Morang upstream (GUPTA et al. 1994). The average annual precipitation in the sub-humid temperate zone varies between 200 and 800 mm, whereas in the semi-arid to arid temperate zone, it is less than 200 mm. The precipitation is in the form of rainfall at the lower altitudes (elevation < 2000 m above msl), snowfall at the higher altitudes (> 2000 m) in the sub-humid temperate zone, and only in the form of snowfall in the semi-arid to arid temperate zone. The minimum and maximum temperatures recorded in sub-humid temperate zone are -8°C and 28°C, whereas in the semi-arid to arid temperate zone -11°C and 15°C (STATISTICAL ABSTRACT OF KINNAUR DISTRICT 1981-2005).

In the recent years, a shift in the climatic patterns in the study area has been observed. Prior to 2000, there were no instrumental records of the precipitation in the area between Morang and Pooh. However, the discussion with the locals confirmed that the said area used to receive precipitation only in the form of snowfall. Rainfall was not observed and only showers for short durations were noted occasionally. The instrumental recording of the precipitation done after 2000 shows that about 120 mm of rain falls in the area annually, whereas the total precipitation is highly variable (Figure 2). It ranged between 257 mm in 2000 and 928 mm in 2002. Thus, this stretch of the area, earlier falling under semi-arid to arid temperate zone, in the present day climatic scenario, can be classified within sub-humid temperate zone.

2 Changes in the Anthropogenic Pressure and Landuse Pattern Contributing to Mass Movement during 1990 ~ 2006

The study area has witnessed a lot of developmental changes during the last sixteen years, i.e., between 1990 and 2006. Two hydroelectric projects, (i) 1500 MW Nathpa Jakhri Hydroelectric Project (NJHP) and (ii) 300 MW Baspa Hydroelectric Project (BHP) have came into being. The NJHP is one of the India's biggest hydroelectric projects with the construction of a 62.50 m high concrete dam at Nathpa. It encompasses 27.39 m long, 10.15 m diameter head race tunnel (HRT) and 982 m long, 10.15 m diameter tail race tunnel (TRT) and 301 m deep, 21.60 m diameter surge shaft. An estimated 3.5 million m^3 material was excavated during the construction which was dumped all along the Satluj River.

120 MW Sanjay Vidyut Pariyojana Hydroelectric Project on the Wangar Gad, a tributary of the Satluj River is already operational in the area. Other hydroelectric projects like 1020 MW at Khab, 400 MW at Thopan-Pawari, 400 MW at Karchham-Shongtong, 1000 MW Karchham-Wangtu and 258 MW at Kashang khad are at the initial stage of their development. All these hydroelectric projects require widening of roads, creation of new township and influx of lot of people in the area, thereby increasing the anthropogenic pressure in the area.

The road network is one of the factors indicating the development in the area. It not only serves as conduit of connectivity, but also provides means of transportation of the heavy machinery to the hydroelectric project sites. It has been noted that the total road length in 1990 was 267 km that increased to 460 km in 2005 showing an addition by 72 % (Figure 3). In addition, the area is traversed by narrow, old and abandoned road, which is aligned about 200 ~ 500 m above the NH-22. Presently, in order to have an alternate route in the area, the widening of this road is also taking place, further increasing pressure in this constrained valley.

The population of the Kinnaur district in 1901 was 27232 with an average decadal population growth of less than 10 % between 1901 and 1951. It rose to about 20 % after 1951, and during 1991 ~ 2001 the growth was about 10 % (Table 1) (STATISTICAL ABSTRACT OF KINNAUR DISTRICT 1981-2005). Along with the increase in local population there is large influx of the skilled and non-skilled persons, working for the hydroelectric projects, from outside. There is thus an ever increasing pressure on the finite land resource in the area.

The change in landuse pattern in the area has also been noted as per the records of the Horticultural department (STATISTICAL ABSTRACT OF KINNAUR DISTRICT 1981-2005). The sharp increase in area under horticultural practices from 3704 to 9432 hectares showing an increase by 155 % during 1990 ~ 2005 clearly depicts that the area under investigation is highly under anthropogenic pressure (Figure 4).

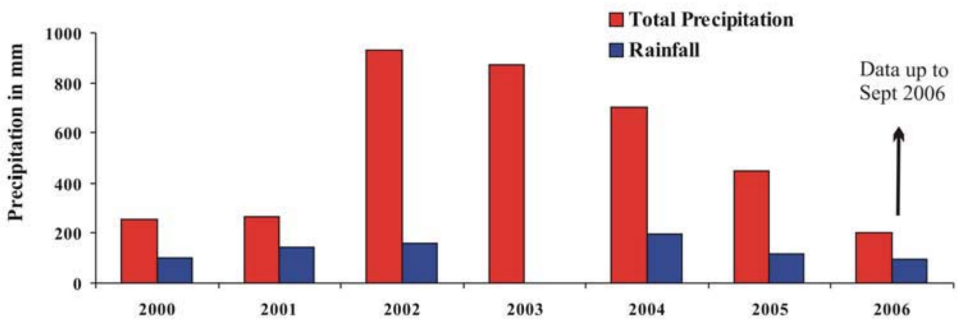

Figure 2 Instrumental recording of precipitation data at Pooh from January 2000 to September 2006

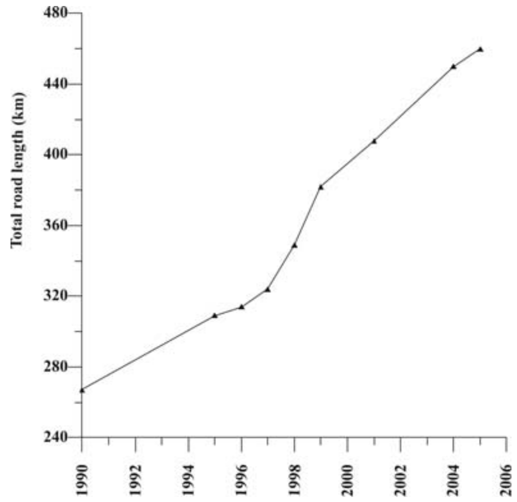

Figure 3 Exponential increase in road length in the study area from 1990 to 2006

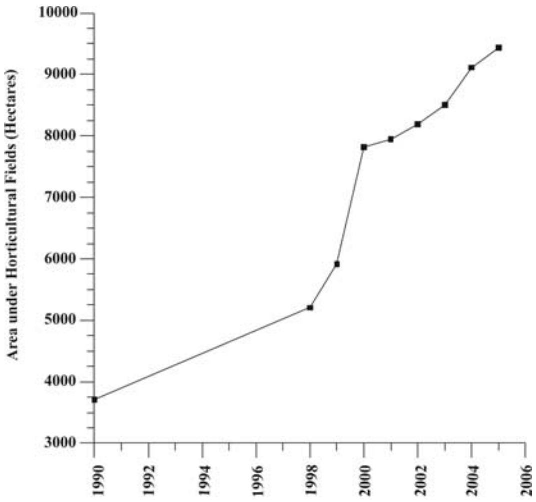

Figure 4 Exponential increase in area under horticultural practices in the study area from 1990 to 2006

Table 1 Population of the Kinnaur district

. N.	Year	Population	% Change
1	1901	27,232	
2	1911	28,470	4.5
3	1921	28,191	-1.0
4	1931	30,445	8.0
5	1941	33,238	9.2
6	1951	34,475	3.7
7	1961	40,980	18.9
8	1971	49,835	21.6
9	1981	59,547	19.5
10	1991	71,270	19.7
11	2001	78,334	9.9

3 Cloud Bursts and Flash Floods Observed during 1990 ~ 2006

The study area witnessed several flash floods along the tributaries of the Satluj River. The most disastrous are 31 July 2000 and 26 June 2005 flash floods. Both the flash floods originated from the Tibetan region were caused by the blockade of the stream course by the landslide, thus creating lakes in the upstream region. The breaching of these lakes caused landslide lake outburst floods (LLOF) in the downstream area (GUPTA and SAH 2007). The area also witnessed LLOFs due to blockade of the Satluj River at Nathpa and

Bhavanager in February and July 1993, respectively. Apart from the LLOFs, the area had also witnessed several flash floods due to cloud bursts. The prominent are July ~ August 1991 along the Malling Nala, September 1995 along the Panwi Khad, August 1997 along the Duling Khad and Wangar Khad, July 2006 along a tributary of River Baspa and August 2006 along Roldang Nala near Ribba.

The unusual high discharge was observed during these flash floods. It was observed that during 2000 and 2005 flash floods in the area, due to constrained nature of the valley, the water level in the river had risen to about to 15 ~ 20 m from normal river level. The discharge was about 10 ~ 12 times as high as the normal discharge during that period (Figure 5). This high energy environment was mainly responsible for the lateral erosion and toe cutting of the slope, resulting into increased incidences of landslides and related activities.

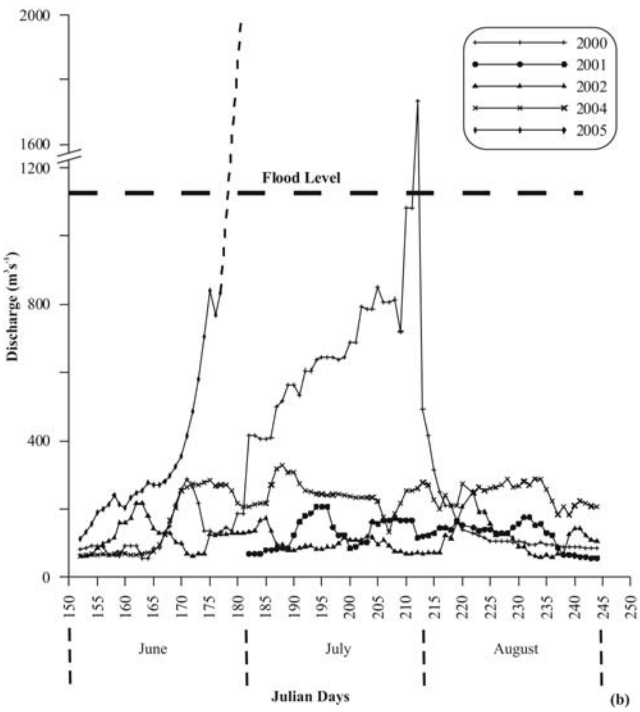

Figure 5 Discharge characteristics of the Satluj River during peak discharge season, i.e., in June, July and August. Note the unusually high discharge in July 2000 and June 2005 landslide lake outburst flood (LLOF).

4 Spatial Variability of Landslides in the Satluj Valley during 1990 ~ 2006

The Satluj valley is known to have had a history of landslides and flash floods during the past. These have been documented during the preparation of inventory maps for paleo- and active landslides (Figure 1 a&b). The context for landslide development in the area is favorable in terms of geological and geomorphological settings (BARTARYA et al. 1996, VIRDI et al. 1995, GUPTA 1998). In this high energy, high relief terrain, the landslides and related mass movement phenomena are natural degradational processes. During 1990s, an inventory of active landslides posing threat to the NH-22 was prepared in the study area (BARTARYA et al. 1996, VIRDI et al. 1995, GUPTA 1998). These are presented in Table 2. It was found that out of the 130 km stretch of the NH-22 exposed in the area, about four km was affected by recurrent landslides every year. These landslides had covered an area of about 1.35 km^2. Most of these landslides were naturally occurring and occur almost every year during or immediately after the rains. All these landslides were mapped based on the classification proposed by VARNES (1978). The common types of landslides are planar debris slides and rockfalls, or a combination of both.

Landslide incidence mapping carried out during 2003, 2004, 2005 and 2006 confirms that the spatial coverage of landslides in the area has increased considerably, covering an area of 11.8 km^2, with an increase by 780 % from 1990 to 2006 and affecting 29 km of NH-22 (Table 2). The increase in the spatial coverage is mainly related to the shift in the climatic pattern, increase in the anthropogenic activity as evidenced by increase in population, total road length and the change in landuse pattern. The succeeding sections describe the change in the spatial distribution of landslides in each climatic zone during 1990 and 2006.

4.1 Landslide distribution in the sub-humid temperate zone

4.1.1 Between Nathpa and Morang villages

The incidences of landslides in the 63 km long stretch between Nathpa and Morang villages are mainly related to bank erosions due to the flash

Table 2 Major landslides located in the Satluj Valley and affecting the National Highway-22 (NH-22)

Sr No	Name of Landslide	Location	Type of landslide	Length of NH-22 affected by the landslide (m)		Spatial area covered by the landslide (km²)	
				During 1990	During 2006	During 1990	During 2006
1	Nathpa Landslide	78°58′21″E; 31°33′45″N	Translational debris slide	350	X	0.070	X
2	Tapri landslide	78°05′47″E; 31°31′09″N	Translational debris slide	X	600	X	0.216
3	Urni Rockfall	78°07′45″E; 31°30′55″N	Rockfall	250	300	0.125	0.15
4	Shongtong Landslide	78°16′42″E; 31°31′29″N	Translational debris slide	X	500	X	0.2
5	Pawari landslide	78°16´00″E; 31°33´30"N	Complex landslide	500	1200	0.5	1.5
6	Telangi Farm House landslide	78°16′03″E; 31°34′58″N	Translational debris slide	X	250	X	0.25
7	Pangi village landslide	78°17′00″E; 31°35′42″N	Translational debris slide	X	400	X	0.35
8	Pangi nala landslide	78°17′20″E; 31°34′30″N	Translational debris slide	300	300	0.0195	0.0195
9	Khadra Dhang landslide	78°22′21″E; 31°35′23″N	Translational debris slide	1300	2000	0.1	0.1125
10	Tirung Khad landslide	78°26′32″E; 31°34′25″N	Translational debris slide	300	300	0.03	0.03
11	Between Morang and Pooh	78°27′00″E 31°36′00″N and 78°34′55″E 31°45′40″N	Debris slide and rockfall	X	15,000 -20,000	X	6
12	Malling landslide	78°37′38″E; 31°51′51″N	Complex landslide	1000	3000	0.5	3

floods in the region. This is mainly because slopes are steep and the Satluj River flows through deep and narrow gorge in this section. The slopes at places are covered with thick veneer of sediments belonging to glacial and periglacial origin. Landslides are present wherever these materials are exposed in the river section, on even moderate slope. This is exemplified by the occurrence of landslides near Tapri, Shongtong, Pawari, Telangi, Pangi and Akpa, which are described hereunder.

(1) Tapri Landslide

The Tapri landslide (78°05′47″E; 31°31′09″N) is located about 200 m upstream of the Tapri Village on the south facing hill slope along the Satluj River (Figure 6). The hill slope gradient in the lower section is about 45° and in the middle reaches it is about 30°. The hill slope essentially is made up of augen gneisses belonging to Wangtu Gneissic Complex (WGC) and is covered with thin veneer of Quaternary deposits in the form of sandy silt with pebbles and boulders of gneisses embedded in it. The lower slope is mostly covered with scattered trees and bushes, whereas, the middle and the upper slopes are covered with horticultural fields and open forests, respectively.

The Tapri landslide first triggered during 2000 LLOF because of the bank erosion of the Quaternary deposit and has been active since then. It is about 350 m long, 600 m wide and 7 m deep, covering a surface area of about 0.25 km^2. The scarp of the landslide is arcuate and is located at 1800 m above msl. It is a typical translational landslide with slip surface trending 35° due south. The rocks encountered in the main body of the landslide are hard and jointed gneisses that dip 45° due NE. The landslide continues to pose threat to the NH-22 and the link road to the Tapri Village. Toe cutting by the Satluj River further adds to slope instability.

(2) Shongtong Landslide

The Shongtong landslide (78°16′42″E; 31°31′29″N) is located about one km upstream of the Shongtong Village on the southeast facing hill slope on the right bank of the Satluj River (Figure 7). The hill slope gradient in the lower section is about 40° and is essentially made up of pebbles and boulders of the mica gneisses embedded in the sandy silt. In-situ rocks are not visible and thickness of this Quaternary cover is about 15 ~ 20 m. The lower part of the slope is covered with scattered trees and bushes, whereas middle slope is gentler and is occupied by agricultural and horticultural fields.

The Shongtong landslide first became active during the drawdown of 2005 LLOF. It is about 300 m long, 500 m wide and 5 ~ 10 m deep, covering a surface area of about 0.20 km^2. The slip surface of this landslide is not clearly visible. However, based on the material involved, it can be classified as a translational debris landslide. It affects about 500 m stretch of the NH-22. Toe cutting by the Satluj River particularly during peak discharge may further adds to the slope instability

(3) Pawari Landslide

The Pawari landslide (78°16′00″ E; 31°33′30″ N) is one of the largest landslides located on the lower valley hill slope along the right bank of the Satluj River near the Pawari Village. The exact date of the initiation of this landslide is not known. However, 1962 Survey of India, toposheet (53J/2), possibly surveyed much earlier, shows the existence of a small landslide. The greater part of the landslide occurred during the construction of Pawari-Pio link road in 1975 and since then it occurs almost every year particularly during the rainy or snow melting season. The landslide has been studied in great details for its geological, geomorphological and geotechnical characteristics by BARTARYA et al. (1996), GUPTA (1998) and YADAV (2000). It was also monitored for surface and sub-surface movements during 1992 ~ 1994 (YADAV 2000).

In 1991, the landslide measured about 1000 m in length, 500 m in width and about 25 m in depth. Many mitigation measures like the construction of retaining walls in the toe and in the main body of landslide proved to be of little help to mitigate the movement. In 2006, the landslide was about 1200 long, 1200 m wide and 25 ~ 30 m deep (Figure 8), thereby increasing the surface area from 0.5 km^2 to 1.5 km^2 from 1991 to 2006 and drastically increasing the width by 140 %. Anthropogenic factors in the form of interference of slope within the main body of landslide as well as improper drainage of the entire Pio township, located just upslope, in the crown portion of the landslide, are the main causes for the increase in spatial coverage of this landslide. The microzonation mapping using lichen coverage has clearly shown three different types of movements within the main body of the landslide (GUPTA 2005).

The Pawari landslide is a typical example of complex landslide, with number of subsidence zones and debris slides within the main body of the planar landslide. The landslide, since its inception, continues to pose threat to the NH-22, particularly during the rainy season. It also greatly affects the subsidence of the Pawari-Pio link road and frequently causes its blockade.

Figure 6 Translational debris landslide located about 200 m upstream of the Tapir Village affecting the NH-22 and the link road to the Tapri Village.

Figure 7 Shongtong landslide located about one km upstream of the Shongtong Village and affecting the NH-22.

Figure 8 View of the Pawari landslide in 2005. It is a complex landslide involving different movements in different parts of the landslide. The landslide greatly increases the width from 500 m to 1200 m during 1990 ~ 2005.

(4) Telangi Farm House Landslide

The Telangi farm house landslide (78°16′03″E; 31°34′58″N) is located on the middle valley slope near the Telangi Village on the right bank of the Satluj River. The general hill gradient is about 40° with the middle slope (about 25°) gentler than the lower and upper slopes. The upper slope is covered with scattered open pine trees, middle with the horticultural fields and the lower slope is barren rocky cliff. The valley slopes are covered with clayey and mica rich soil exploiting from the highly weathered parent mica gneisses. The thickness of the soil cover, as evidenced in the cut section is more than 30 m.

The exact date of the initiation of the landslide is unknown, however, the activity of this landslide was more pronounced after 2000. It is a translational debris slide with slip surface trending due east. Number of subsidence zones within the main body of landslide has been observed. The total length of the landslide stretching from the HT road section to the Satluj River is about 700 m, whereas the width is about 200 ~ 250 m, covering a surface area of about 0.25 km². The scar of the landslide is located at 2590 m. The height of the scar varies from 3 m to 5 m (Figure 9). Transverse cracks are observed at an evevation of 2413 m, 2404 m and 2396 m. These cracks are segmented and run almost N-S direction along the width of the landslide. The cracks are about 15 ~ 20 m long, 1 ~ 1.5 m wide and about 3 ~ 3.5 m deep. In order to avoid any infernal happenings, most parts of the cracks have been grouted by the local people. The landslide continues to pose a threat to the Telangi-Pangi link road, horticultural fields along with few residential buildings of the Telangi Village.

The landslide was visited regularly in 2004, 2005 and 2006. The activity of the landslide was noted to be more in 2005, but in 2006, no movement was reported after grouting the cracks. It is important to note that an unlined canal measuring 65 cm wide and 10 ~ 15 cm deep runs all along the width of the landslide at an elevation of 2572 m. The continuous seepage of water from this canal might have increased the pore water pressure of the mica rich soil that could be one of the reasons for the occurrence of the landslide. However, in 2005, in order to minimize the ingress of water into the slope, the canal was replaced by closed drainage.

(5) Pangi Village Landslide

The Pangi Village landslide (78°17′00″E; 31°35′42″N) is located very close to the Pangi Village in the middle, east facing valley slope (Figure 10). The general hill slope gradient is about 40° with the middle slope gentler than the lower and upper slopes. The lower slope is barren exposing jointed and sheared micaceous rocks belonging to the Vaikrita Group. The general slope gradient in this section is about 70° ~ 90°. The middle slope is covered with agricultural and horticultural fields, and also with thin veneer of soil extracting from fine grained gneisses with bands of biotite gneiss. Three prominent sets of joints trending 70° due NW, 45° due NE and 70° due SW along with the 60° due S70°E foliation joint are present in the area. The joints are tight and the spacing between joints varying from 25 cm to 100 cm has made the entire rock mass weak. The rock mass crumbles as it comes in contact with water because of the presence of high mica content.

The Pangi Village landslide first triggered in 2004 possibly because of the widening of the road, and has been active since then (Figure 10). The widening of the road was done by conventional method of drilling and uncontrolled blasting, resulting breakage of the entire rock mass into smaller pieces. It is a typical translational debris slide with slip plane dipping 55° towards east. The landslide measures about 800 m long, 400 m wide and about 7 ~ 10 m deep, covering a surface area of about 0.35 Km². The extension of the landslide is visible on the NH-22 affecting about 400 m long stretch.

(6) Khadra Dhang Landslide

The Khadra Dhang landslide (78°22′21″E; 31°35′23″N) is one of the major landslides on the right bank of the Satluj River near the Akpa Village (Figure 11). The landslide first triggered in early 1960s, and since then it has taken place almost every year during the rainy season, damaging the NH-22 passing through the toe portion of the landslide. It is a typical translational debris slide that occurs in the lower and middle hill slopes. The general gradient of the lower and middle hill slopes is 30°, and these are covered with agricultural fields, whereas the upper slope is about 40° and is covered with open forest. In 1991, the landslide measured 75 m in long, 1300 m wide and about 10 ~ 15 m deep, covering a surface area of about 0.1 km². The material involved in the sliding is semi-consolidated glacial debris. The thickness of this debris is about 40 ~ 45 m as is evident in the cut section. The entire material is highly prone to landslide due to bank erosion. However, during 2005 ~ 2006, the width of the landslide increased to about 2000 m with increased number of subsidence zones in the main body of the landslide. The bank erosion in the form of toe cutting by the Satluj River is the main cause of the spatial increase in landslide coverage.

In order to avoid the landslide, the National Highway was diverted on the left bank of the Satluj River by constructing two bridges near the Kharo Village and the Akpa Village. The valley slopes between Kharo and Akpa are also comprised of semi-consolidated glacial debris. The road is cut through this material at the toe of the slope making the entire slope unstable and series of small scale landslides have been generated in this section (Figure 11). However, the massive bank erosion during 2000 and 2005 LLOFs has been reported in this section that damaged both the bridges and the entire 2 km road section between Kharo and Akpa. The bridges were rebuilt at the same location and the new road was made by cutting the hill. In the present scenario, because of the continuous bank erosion by the Satluj River, the entire lower valley slopes are unstable, posing serious threat to the people living in the area.

4.1.2 Between Morang and Pooh

The valley slopes in the 32 km long stretch between Morang and Pooh are invariably steep, with the middle valley slope gentler than the lower and upper valley slopes. The lower and upper valley slopes are barren and range between 60° ~ 80°. These mostly comprise jointed and sheared mica schist and slate interbanded with quartzite belonging to the Haimanta Group. Four sets of joints trending 40° due S30°W, 45° due N40°W, 60° due S20°E and 60° due E in the area have made the entire rock mass very weak. The middle valley slope is covered with thick veneer of sediments and is occupied by dense horticultural fields.

Figure 9 Scarp of the Telangi Farm House Landslide which is about 3 m high.

Figure 10 Translational debris landslide located near the Pangi Village in the middle valley hill slope. The landslide involved highly fractured and sheared biotite gneisses and greatly affected the road traversing the main body of the landslide.

Figure 11 Khadra Dhang landslide located on the right bank of the Satluj River. The new alignment of the NH-22 on the left bank of the river, has made the entire hill slope unstable.

Figure 12 Unstable hill slope showing the initiation of landslide near Spilo in the Morang-Pooh section.

There was a marked difference in the landslide activity in the Morang-Pooh section between 1990 and 2006. This is primarily because of the shift in the climatic patterns in the area. During 1990s, this section was completely dry and not affected by rainfall. The slopes were steep and stable under the dry condition. However, in the recent years, rainfall has invaded the area towards north and northeast direction, showing its influence upto Pooh. The rainfall data collected at Pooh for the years of 2000 ~ 2005 shows that the area received about 120 mm of annual rainfall dominantly between March ~ May and August ~ September. This renders the entire stretch between Morang and Pooh highly unstable (Figure 12). Number of new landslides in the area have been observed. Each year, new small-scale landslides in the area are added. Most of these landslides are in the form of rockfall, rock and debris slide, endangering the NH-22 passing through the lower hill valley slope. The entire valley slopes in the area are unstable under the wet condition, and will continue to slide down, until an equilibrium is achieved.

4.2 Landslide Distribution in the Semi-arid to Arid Temperate Zone

The Malling Landslide zone (78°37′38″E; 31°51′51″N) located along the Malling Nala on the left bank of the Spiti River is an old landslide. The exact date of the initiation of this landslide is unknown. However, the Border Road Organization (BRO) record shows that the landslide occurs every year since 1970, particularly in summer when the snow melt discharge in the Malling Nala is maximum. Geologically, the entire slope comprises highly jointed, fractured and weathered micaceous schist along with thick band of pegmatites belonging to the Tethyan sequence. The slopes in the area are mostly barren and range between 40° ~ 50°, with the middle part of the slide zone is steeper than the upper and lower parts.

During 1990s, the Malling Nala landslide zone measured about 500 m long, 1000 m wide and about 10 ~ 15 m deep (Figure 13). The NH-22 was located on the lower slope of the landslide about 150 m above the Spiti River. There was a continuous seepage of water from the Malling Nala, which could be seen in the form of water oozing out from the slopes. The continuous percolation of water into the micaceous schist has made the entire rock mass susceptible to landslide as well as subsidence. Number of subsidence zones was noted around the NH-22 and every time new alignment of road was made by cutting in-hill the slope. In 2005, the dimension of the landslide zone measured about 1000 m long, 3000 m wide and about 15 ~ 20 m deep, thereby increasing the surface area from 0.5 to 3 km². Anthropogenic activity in the form of interference of slope, mainly for the excavation of road is the main cause for the spatial increase in coverage of landslide. Each time, new alignment of road is excavated, landslide increases in dimensions.

In order to avoid the recurrent landslide, in 2000 a new alignment of the NH-22 was made on the upper valley slope at an elevation of 3650 m. This has further added instability to the entire slope length.

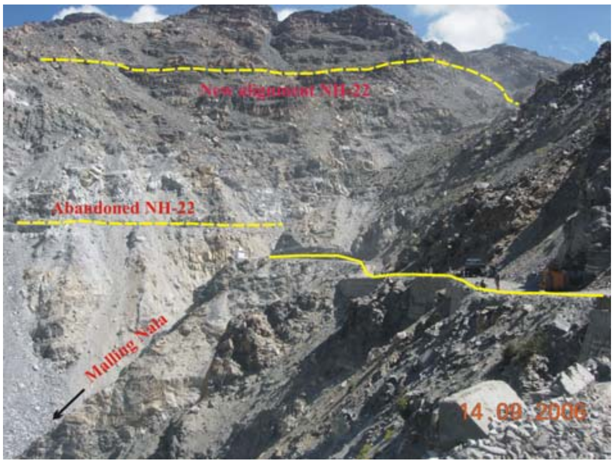

Figure 13 Malling Nala landslide zone located on the both sides of the Malling Nala. The continuous seepage from the Nala has made the highly jointed, sheared, and crushed country rock to slide down, making the entire hill slope highly susceptible to landslide.

5 Discussion and Conclusions

The hazard mapping indicates that the Satluj Valley has a history of flash flood and related mass movement activities since geological times (GUPTA and SAH 2007). This has been well exemplified by July 2000 and June 2005 LLOF along the Satluj and Spiti rivers.

The present study demonstrates that there was a significant increase from 1.35 km^2 in 1990s to 11.83 km^2 in 2006 in the spatial coverage of area falling under landslides. Out of 130 km length of the NH-22 exposed in the area, there was an increase of 621 % length affected by the landslides from 4 km to 28.435 km during 1990 ~ 2006. Inherent geology, in the form of highly jointed, shattered and sheared rocks with Quaternary cover combined with natural as well as human induced factors constitute a propensity towards the increased spatial coverage of landslides in the area. Among the natural factors, particularly between Morang and Pooh, the shift in the climatic pattern in the form of north- and northeastward penetration of rains is the primary factor. Similar type of rainfall migratory trends has also been noticed in Central Himalaya (RENOJ et al. 2005). This has resulted into more area to fall under the influence of rains. The valley slopes in the Morang-Pooh section were barren, steep and were made up of highly jointed and sheared micaceous schist. These slopes were stable under the dry condition. However, under the influence of water, the micaceous schist crumbles, making the entire slope unstable. Each year after 2003, new landslides have been generated and it is expected that in the future, if the climate patterns would continue to remain the same, the steep slope between Morang and Pooh section would be reduced to an angle commensurate with the climatic conditions.

Human induced factors also play an important role in the increased spatial coverage of landslide. Among these are the excavation of the slope for new road cutting and settlements, road widening by conventional method of drilling and uncontrolled blasting, increased population pressure, changing landuse patterns in the form of increased area falling under agricultural and horticultural practices.

It is also suggested that wherever glacial material is exposed, even on moderate slope, slope instability has been recorded because of the toe erosion, particularly during high discharge. This renders the entire slope length highly susceptible to landsliding. This is borne out by the field examples near Tapri, Shongtong, Pawari and Akpa.

The outcome of this study has two major implications related to the increased developmental activities and the climate change in the area. With the increased developmental activities, mainly related to coming up of hydroelectric projects, the increased number of landslides, in turn, will pose threat to any development in the area. Secondly, the increase in the spatial coverage of area falling under the influence of rains, not only increases the number of landslides, but also increases the sediment load in the rivers, thereby damaging the hydroelectric projects located downstream in the area.

Acknowledgements

The authors thank the Director, Wadia Institute of Himalayan Geology, Dehra Dun for extending all the facilities and permission to publish the paper. We also express our thanks to the Himachal Pradesh State Electricity Board, Jai Parkash Industries Ltd., Satluj Jal Vidyut Nigam Ltd., Kinnaur District Administration, Border Road Organization and the local people for sharing the information and extending all possible help in the field.

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