GIS in landslides susceptibility mapping, Murree area, north Pakistan

Abstract

This paper presents a GIS-aided procedure for landslide susceptibility mapping. The base map is prepared by visiting the field area and mapping individual landslide at a scale of 1:50000 topographic maps. A number of parameter maps are prepared by collecting information from various authorized sources and converting them in to GIS maps. The susceptibility assessment is based on multivariate statistical techniques, which is tested on the study area situated in the east and northeastern part of Murree town, north Pakistan. The study area is famous for being one of the most important resorts of Pakistan. The results obtained using a random sample show that 95% of cells have been properly classified. The minor inaccuracies are attributed due to unavailability of accurate maps for deriving the Digital Elevation Model (DEM) and other factor maps. The result shows that the inherent vulnerability of the study area is because of both natural and man induced activities.

Introduction

Murree area is one of the most famous summer resorts of Pakistan. The paper focuses on part of Murree area situated at 33° 52' 35.706'' to 33° 59' 57.804'' degree latitude and 73° 24' 21.156'' to 73° 31' 4.8119'' degree longitude. It suffers largely from the landslides activity during the heavy showers of Monsoon season and some occasional heavy rains during the months of January to March. The rainwater increases the pore water pressures reducing the soil strength, which is eventually overcome by the slope driven forces.

Susceptibility mapping of landslides is described by determining the vulnerability of study area to landslides and other mass movement processes by statistically correlating the major factors causing landslides in an area. These maps serve as a basic tool for land use planning. Previously the study area was studied more with respect to landslide distribution and qualitative hazard zone mapping (Abbasi I. A. et al., 2001). The paper attempts to prepare the landslide hazard map for the study area by compiling the previous work and preparing the landslide distribution map and other geological data through field visits for individual landslides. The landslide distribution data is latest by June 2005.

Geological setup

One of the most important factors contributing to the landsliding in study area is its complex geological and tectonic setup. Murree area occupies part of Himalayan foothills and Himalaya was created by collision of Indian plate with the Eurasion plate during Eocene time along a suture zone known as the Main Mantle Thrust (MMT) (Tahir kheli et al., 1979; Coward et al., 1986), and is the most rapidly uplifting region on earth (Zeitler, 1958). The deformation progressively migrated southward away from the Early Eocene collision zone at the MMT and reached the Himalayan foothills by Miocene time. The Himalayan foothills also know as sub-Himalayas (Gansser, 1964) are defined as a set of rocks which are bound by major thrust faults such as Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT) to the north and south respectively. Murree area lies in a seismically active zone due to its proximity with the active Murree Thurst (local name of MBT). On average earthquakes of intensity 4–5 are recorded on Richter scale.

The molasses sediments (siltstone and sandstone) of Murree and Kuldana formation (Oligocene-Miocene) constitute most part of the Murree Hills. The sandstone of the Murree Formation is red to reddish gray in color, multistoried, fine to medium grained, cross-bedded, hard and compact constitutes 4-6m thick sequences that occasionally attain thickness of over 10m. The sandstone sequences are interbedded with red color, 10's of meter thick siltstone and shale. These fine-grained facies constitute more part of the formation and provide a weak zone for most of the faults to propagate through it. Landsliding and other mass movement phenomenon are inherited to the area due to weak component lithologies, complicated and intense deformation compounded in recent times by anthropogenic factors like deforestation, construction and over-population etc (Neiderer and Schaffner, 1989).

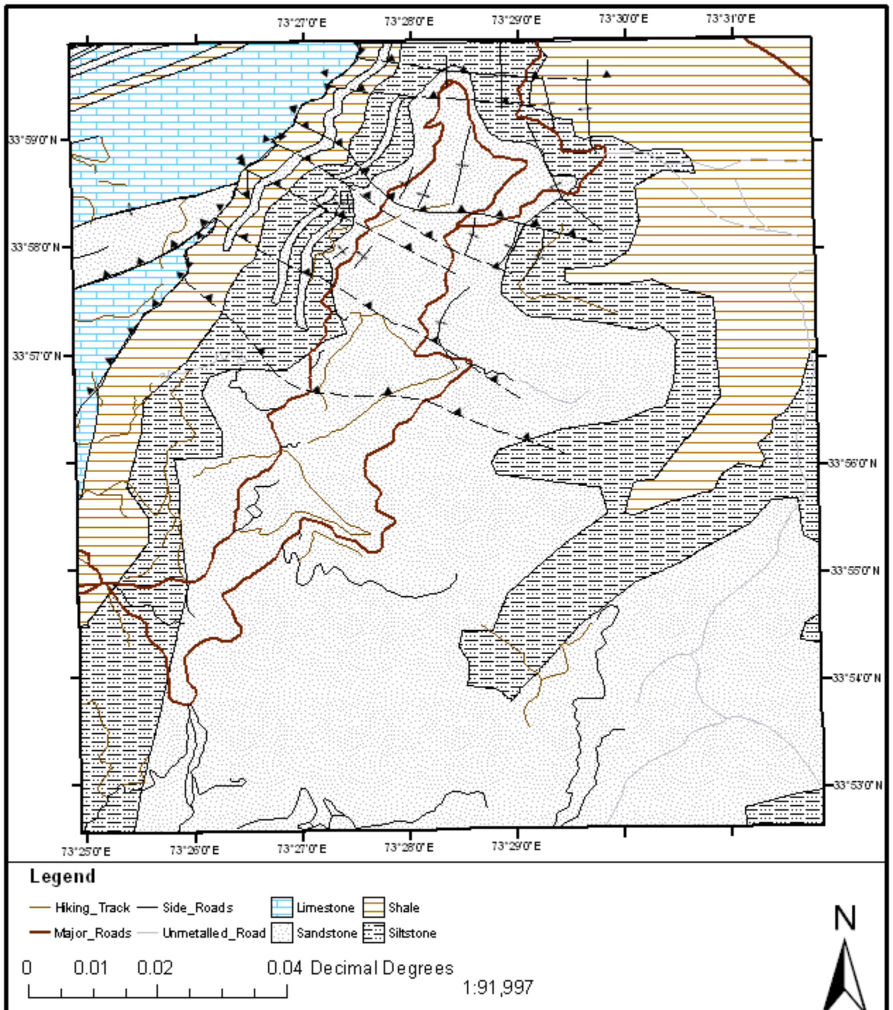

Figure 1. Geologitcal map of the study area

Structurally the study area is complexly deformed by MBT and the folder associated with it (Chambers, 1992, Iqbal and Bannert, 1998). The Murree Thrust trending NE-SW, is an emergent fault passing close to most of the landslides in the study area. Most part of the central ridge on which the Murree Town is located is a SW plunging syncline with the Murree Formation lying in the core of the syncline, and the beds dipping inward towards the core of the ridge. This structure provides a degree of structural stability to the ridge. At the same time, combined with a lithological setup of alternating sandstone-siltstone-claystone layers, this structure makes the Murree ridge a major reservoir of water. This is evident from the presence of many springs and seepages at the toes of major sandstone horizons (Rafiq et al., 1989). This seepage often facilitates slippage of rock and soil bodies at slopes and thus contributes to mass movement.

Detailed field investigation was carried out to prepare a comprehensive geological map of the study area (Fig.1). The geological map was prepared at a scale of 1:50,000 to map major as well as local details. Survey of Pakistan toposheet No. 43G/5 and 43G/9 were used as a base map. A number of previously published maps (Lateef, 1971; Chambers, 1992; Iqbal and Bannert, 1998) were used to compile and refine the present map.

Land-use

The area to the east of Murree town is dominantly under pine forest cover, particularly along the major roads and upper reaches of the ridges. A number of recreation spots, parks and hotel resorts are located in the area. Ever increasing population and large number of visitors pouring in every summer has led to increased use of land for residential purposes. Villages are spreading fast and there has been a large increase in newly built houses every year. Terraced slopes are widely used for cultivation, particularly in the lower and middle reaches of the slopes. A preliminary landuse map has been prepared for the area based on the compilation of existing work and through field visits (Fig.2).

The area can be divided into two catchments, the western Kaner Kas catchment and eastern Aliot Kas catchment. NE-SW oriented Upper Topa-Kashmiri Bazar-Bhurban ridge is the drainage divide. A large part of the area is in the form of agricultural terraces particularly the low angle terraces. These terraces are maintained well and are irrigated by rainwater (mostly during monsoon season). Vegetation in the form of pine and broad leave trees is common all over the terraces. Thick pine forest is preserved along the ridge tops and up-slopes. Colluvium cover is thick and better preserved along the terraces and forested areas, but lost from the barren area and streambeds.

The landuse map shows that the lower reaches of the ridge, particularly along the major streams such as Kaner Kas and Aliot Kas are barren without any vegetation cover. These areas are vulnerable to mass movement process, particularly along the Aliot Kas. The area along the left bank of the Kaner Kas is relatively stable due to comparatively more competent lithologies such as limestone exposures. These are grouped as barren land that constitutes about 20-25% of the area. Forests including both pine and broadleaf fruit trees constitute a major part of the land cover.

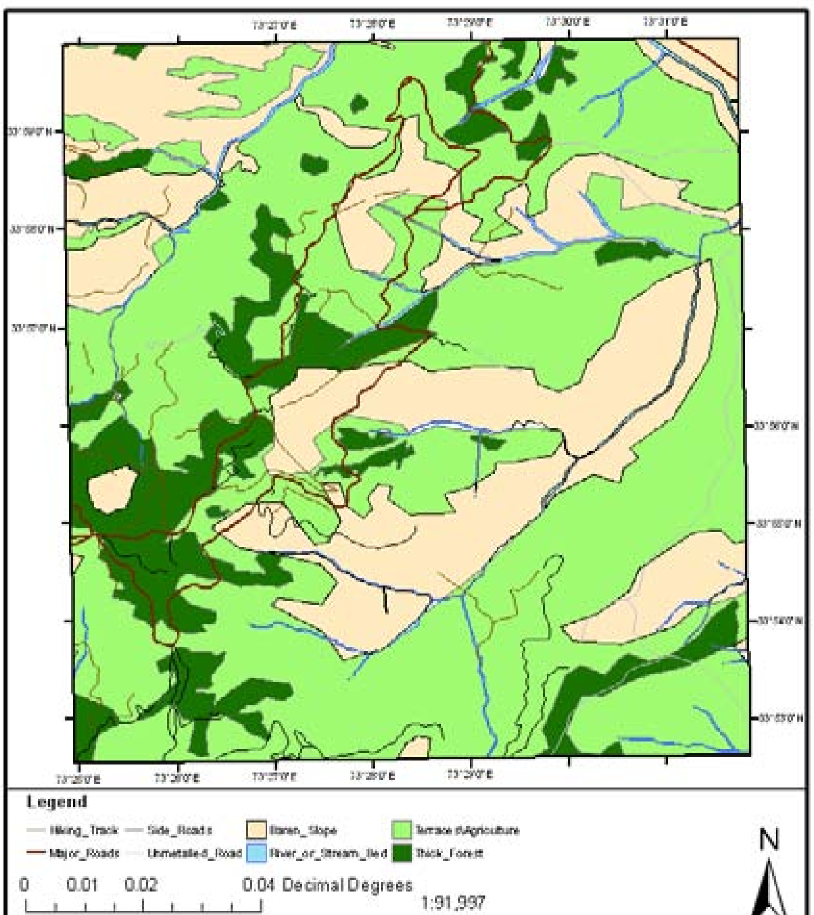

Figure 2. Landuse map of the study area.

Analysis factors

Topography

The hill slopes in the Murree area are moderately steep (Fig.3). The slope angle varies from 40-50º in the upper reaches and 30-35º in the middle and lower reaches. An increase in steepness or slope gradient leads to an increase in shear stress on the potential failure plane and a decrease in normal stress (Malik and Farooq, 1996). In the lower most reaches on the northeastern side of the Murree ridge along the Aliot kas, the slopes are exceptionally steep on both sides of the stream due to rapid down cutting of the stream bed, and large landslides are located along the stream banks.

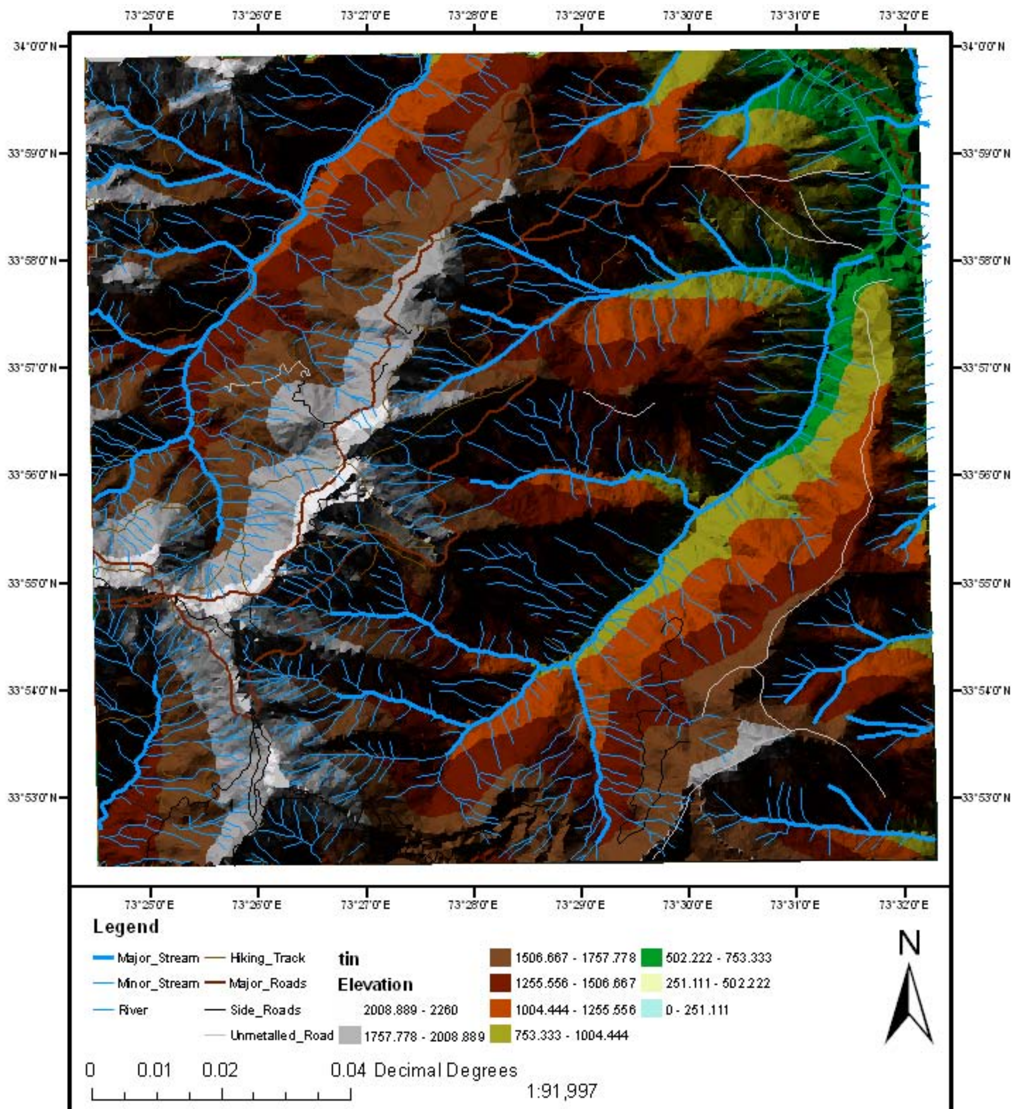

Figure 3. Digital elevation model (DEM) of the study area.

Climate

Pakistan lies on the western margin of the monsoon region, while Murree hills lie in the climatic division of sub Tropical Continental Highlands. Vast variations in climate are caused by the differences in altitude, amount of winter snowfall, and duration and depth of the snow

accumulation. Generally the climate is cooler at higher altitude and warmer at lower ones. Spring and autumn are short.
Murree receives 1700 mm of annual precipitation in the form of rain and snowfall in approximately 89 mean rainy days, however, different parts of the area receive varying amount of rainfall. The bulk of precipitation is received during the monsoon in July and August when the rainfall is usually in heavy bursts. The mean monthly rainfall varies between 33mm in November and 351mm in July. In winter snow falls above an altitude of 1200m, and persists above 1800m during January and February, especially on cooler slopes. The humidity varies between 80% in August to 27% in May.
Landslides most commonly occur during monsoon time; however, some damage is also associated with snowmelt during springtime. The onset of monsoon does not trigger landslides; instead it increases in the later part as the successive rainfalls first wet the dry slopes and then saturate the materials in their depth (Malik and Farooq, 1996). An increase in moisture content on a potentially unstable slope plays a deciding role in triggering a mass movement by decreasing the shear strength of the material. Although the sandstone of the Murree Formation shows a decrease of about 20% in its strength due to moisture but the interbedded silt/claystone show substantial decrease in strength due to remolding (Malik and Farooq, 1996).

Earthquakes

Energy in the form of seismic waves is released when an earthquake occurs. These seismic waves while traveling through the ground accelerate the movement of the ground and produce dynamic loads, increasing pore-water pressure and shear stresses in the slope (Malik and Farooq, 1996). The Murree area lies in a seismically active zone due to its proximity with the active Murree Thrust along which magnitude 4.5 to 5.0 earthquakes on the Richter scale have been recorded as recently as 1977, nevertheless, earthquakes of magnitude 6 or even 7 can be expected along this zone.

Human Factor

Besides the natural agents, there are several human induced factors, which undermine the stability of slopes and play an important role in accelerating the mass movement phenomenon. These include;

Population

The population growth trend in Murree has been inconsistent since independence. Despite a general trend of local people to shift to other parts of the country in search of jobs, the population kept on increasing due to natural growth, attraction of pleasant climate in summer and recent developments. The population is increasing about 3.1% yearly and has led to a densification and outward expansion of villages. Agriculture is becoming increasingly less viable, forcing farmers to plant more orchards especially apple trees on their land (Urs and Schaffner, 1998). The fuel and fodder needs of a burgeoning human and livestock population results in indiscriminate cutting of trees and uncontrolled grazing which has caused severe land degradation and erosion problems. On top of that about three quarter to one million tourists visit Murree every year and is increasing on average by 5% yearly. There are estimated to be over 500 small and large hotels to cater for the needs of these tourists. A major problem associated with the population growth and development of tourist facilities is the improper disposal of the waste and rainwater, which is further aggravating the erosion problem in this area.

Deforestation

Murree Hills were once covered with thick forest with all ages of conifer and broad leave trees and shrubs. This vegetation cover used to provide maximum slope stability and protection against erosion. With increasing population, the forest was thinned out by fire and grazing, cutting of timber and firewood and cultivation of new lands. This along with the construction of new houses and roads led to a significant loss of natural vegetation cover (Urs and Schaffner, 1998). During last fifty years the number of houses and their height has doubled and the road has been widened cutting further into fragile slopes. As the root network is lost, the colluvium deposits as well as the shale or softer rocks tend to disintegrate rapidly. Bare slopes can hardly withstand the devastating effects of fast surface runoff after heavy rain bursts and fail regularly loosing the soil cover, and finally develop into landslides.

Drainage System

An adequate drainage system is of vital importance for slope stability and infrastructure maintenance. The system of surface and ground water drainage is almost non-existence or greatly inadequate in the Murree area. During precipitation the water runoff is not only uncontrolled but is also obstructed by unplanned construction work.
There are no adequate and proper roadside drains and where present are filled with debris, which are rarely cleaned. At places the channels constructed for water diversion on major landslide were subsequently broken due to later movements but have not been repaired.

Unplanned Construction

During last two decades, promotion of tourism in the area increased values of land many folds. Increased influx of tourists has led to construction of residential hotel, shopping centers, recreation centers and concrete houses with modern sewerage system has seriously disrupted the natural drainage system of the fragile slopes. A large number of multistoried buildings are cropping out all over the town without any regard to Murree bylaws, putting tremendous pressure on slope tops. A number of new housing schemes are being developed without proper consideration of slope stability of the area. The sewerage waste of residential, commercial and cantonment areas is a serious threat to the slope stability and also to the settlements down slope. One such problem is right below the cantonment area of Garial camp where local people complain about the lack of interest of the cantonment/military authorities for taking care of their sewerage system, which has led to a major landslide threatening the village of Nirgoli downhill.

Excavation of Slopes

Excavation of slopes, particularly the toe of slope for building of new roads, widening of the existing roads and construction of houses and other buildings is a common phenomenon in this area. It is a source of earning for some of residents who dig into the hills without proper arrangement and thus causing instability. This destabilizes the existing state of stresses and promotes landslides. Similarly dumping of waste or excavated material on hill slopes is a common practice in these areas adding load on hill slopes.

Landslide distribution map

In order to study landslides and related mass movement problems, an area to the east and northeast of the Murree town is selected for detailed analysis. The area is located between Jhika Gali-Bhurban and Jhika Gali-Aliot sections (Fig.4). Landslides map was produced first by studying existing landslide distributions maps (Niederer et al., 1989; Rafiq et al., 1989) and by visiting the field area and recording individual landslides sites with the help of GPS. Current landslide distribution data is updated by July 2005. The area is divided in to different sections with respect to landslide distributions as follow.

Jhika Gali-Lower Topa section

This section is part of the reserve forest and has a good vegetation cover, mostly pine forest. The colluvium cover is thick and is supporting the vegetation well. Creep, however, is common at a number of places particularly on the valley side of the road. Rock outcrops such as sandstone and siltstone are exposed along road cuts at places.

Lower Topa to Nirgoli Section

Despite reasonably good vegetation cover, the area is affected by a number of landslides damaging the road as well as the forest. Important landslides identified in the area included the

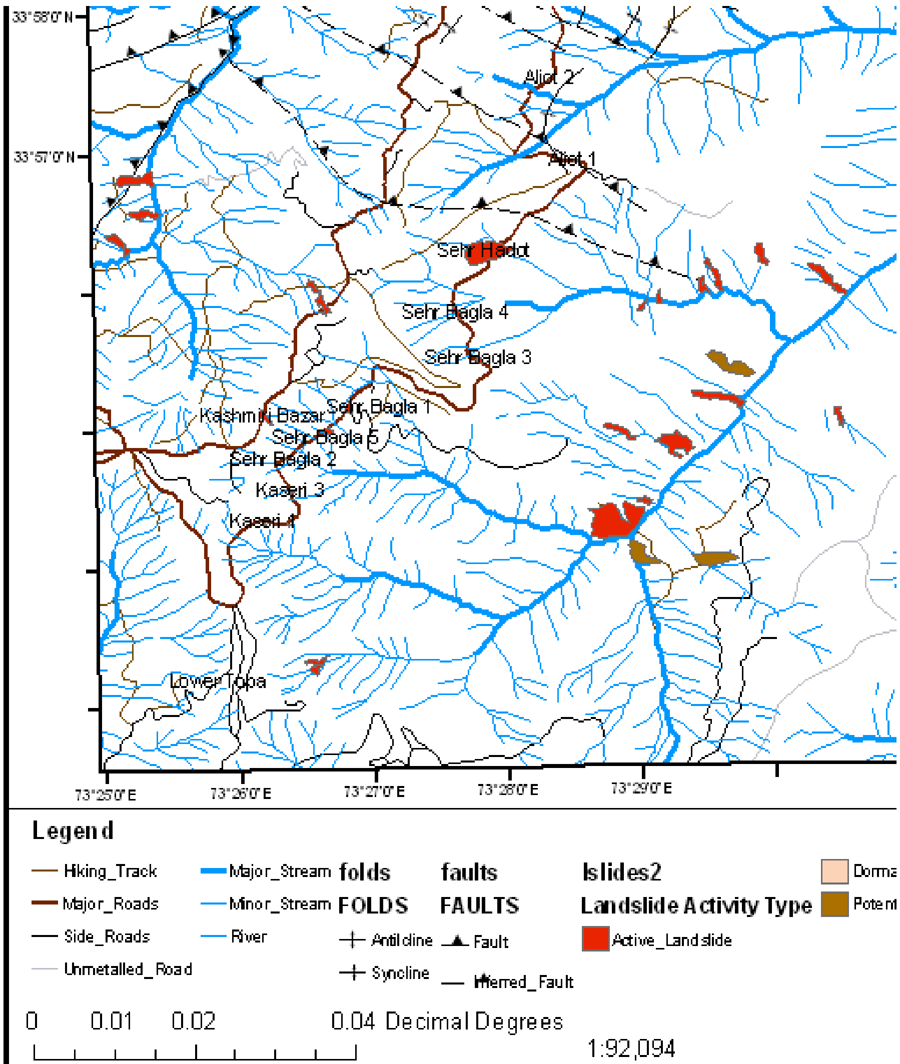

Figure 4. Landslide distribution map of the study area.

Nirgoli landslide, which is dormant now due to stabilization works such as retaining walls, gabions and channels. Vegetation in the slide area has also helped to stabilize it. A number of landslides are located along the stream banks, which have been active since very long time. Some of these have attained a degree of stability due to bedrock exposures.

Nirgoli to Aliot Section

This is probably the most unstable area due to landsliding and is potentially hazardous. Some of the most devastating landslides such as Sehr Bagla, Sehr Hadot, Birgran, Kaseri and Aliot landslides are located in this section. High angle slopes in the area are generally unstable due to poor drainage and weak lithologies. The area is comprised of siltstone and sandstone of the Murree Formation and supports moderate to good vegetation. Aliot landslide is the largest slide in the area, which is well over 1km long and has disrupted major part of the village, and also is a constant threat to the main road. This area is densely populated and a number of houses are located in the unstable areas.

Aliot to Dewal Section
The area further to the east of the Aliot is relatively stable due to thick forest cover. Two large active landslides associated with the stream erosion occur in this area caused by sudden increase in the slope angle and complex structural pattern of the strata. The lithologies are comprised of siltstone and clay with rare sandstone interbeds. The banks of the Aliot Kas (stream) are most unstable and a number of large landslides are located along it.

Jhika Gali to Kashmiri Bazar Road Section
This is an increasingly unstable road section. Creep is common in colluvium cover along most of the stream cuts, with slope failure at a number of places. Retaining walls are broken due to this movement. The downslope of the road section has become in the form of a concave valley due to sinking and sliding. A number of trees are fallen on the sides of the elongated depression about 50m wide. Young trees are growing inside this zone. This probably is part of an old landslide. Apart from a number of other unstable zones, major unstable area in the form of a landslide is the Aliot and Kashmiri Bazar landslide.

Factor maps
Several terrain parameters related to the occurrence of the slope failures have been selected for their inclusion into the multivariate statistical analysis. Variables not derived from the DEM were obtained by means of fieldwork and compilation of existing work done (land use, thickness of the superficial formations and landslide inventory). This information was digitized and then converted into raster format to carry out the analysis. Precipitation is the main triggering mechanism of shallow landslides in the study area. Several researchers have found an increase of rainfall with altitude and a consequent increase in the number of slope failures. The slope angle is the main geometric instability. The higher the angle the greater is the shearing component of the forces acting at the potential surface of failure. The geological and morphological diversity of the study area has a particular effect on the threshold angle for slope failures. The latter occur in colluvium blanketed slopes or on weathered argillaceous formation. It appears that, even though a minimum angle is needed to cause slope failures, such failures are absent on very steep slopes (over 45.). This is because neither colluvium nor weathered clay can stand on these slopes. Steep slopes are made of resistant bedrock and are stable. High roughness slopes are more prone to landsliding because gradient changes favor rainfall infiltration into the soil. The slope curvatures indicate the capability of water run-off concentration or dispersion. Several studies suggest that shallow landslides mostly occur in topographic hollows where subsurface flow concentrates (Reneau and Dietrich, 1987). The watershed area is related to the amount of water that the soil can collect and infiltrate. A greater area is associated with more water infiltrated and higher chances of landsliding (Oyagi, 1984). The length of watershed indicates the size of watershed area, the capability to concentrate groundwater and to accumulate sediments. A close relationship has been found between the distance to water divide and location of the slope failures (Oyagi, 1984). Both area and length of superficial deposits show the extent where the water may infiltrate into the material susceptible to failure. Finally, the mean slope angle of the watershed indicates the capacity to help water infiltration into the soil. Land use (density of vegetation) has a twofold influence on the stability of superficial deposits: hydrological (capacity of infiltration into the soil, soil moisture, groundwater level, etc.) and mechanical (root strength) (Greenway, 1987).

Susceptibility map
The hazard map (Fig. 5) is synthesis of geological, slope in degrees, slope direction (aspect), drainage, roads network and landuse maps. This map is classified into four categories i.e.,

- Very High Hazard
- High Hazard
- Moderate Hazard

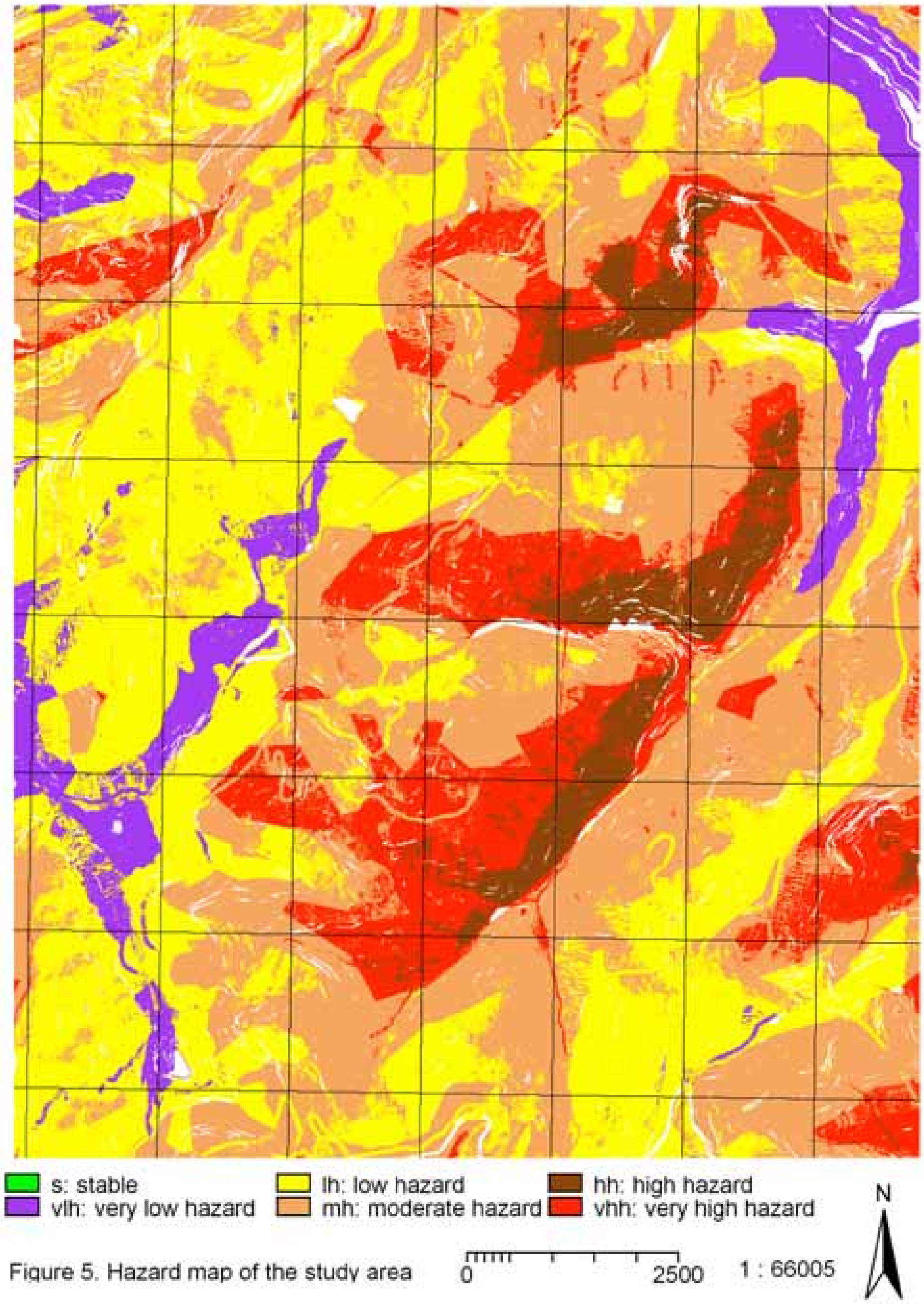

Figure 5. Hazard map of the study area

- Low Hazard
- Very Low Hazard
- No Hazard or Stable

The map shows that the area with highest risk is located along the Aliot Kas and along parts of the Jhika Gali-Aliot road sections. The very high hazard areas constitute about 15% of the total area. About 40% of the area is vulnerable to moderate risks mostly in the Aliot Kas catchment. Most of area in the Kaner Kas catchment and along the Jhikka Gali-Burbhan road section is under moderate to low hazard.

Much of the studies in Murree area have been restricted to active and thus obvious zones of landsliding. From the compilation of field data using GIS packages an attempt is made to mark not only the active but also dormant landslides and potentially unstable areas. Every year government spends a lot of money to stabilize affective area. These areas acquire some degree of natural stability and thus host vegetation cover similar to the stable areas underlain by intact bedrock. During developmental work particularly during excavation at the foot of the slopes, these areas due to their high mean porosity and high water content are vulnerable to reactivation when the slopes are disturbed at their toes.

Apart from a number of small landslides, the Nergoli-Aliot-Dewal Road Section is affected by a number of major landslides such as Aliot, Sehr Hadot, Kaseri, Dehla and Nergoli landslides. Major cause for these landslides is improper drainage system, road under cutting, improper excavation, sudden change in slope angle and the complex geology of the area. Sehr Hadot and Dewal, which are the largest landslides in the area, have been triggered due to inadequate waste and rainwater disposal from the Jhika Gali-Kashmiri Bazar ridge in the landslide area for a long period of time.

Discussion and recommendations

This study shows that the major mass wasting process in Murree area is land sliding, triggered mainly due to combined effects of natural causes such as inherited lithological and structural weaknesses and high precipitation rate, and man made effects such as deforestation, large scale construction activities and poor drainage. Murree being the most developed summer resort of the country is subjected to tremendous development activities leading to construction of new roads and widening of old ones, such as Rawalpindi-Kashmir road, Bypass road etc. Similarly large housing schemes such as MIT Housing scheme on the eastern slopes of the Murree ridge are focus of large-scale construction activities in the form of multistoried houses and apartment buildings.

The instability in the Murree area is partly due to its inherited geological characteristics and climatic conditions, and partly due to human factors. It is difficult to overcome the natural causes but it is greatly needed to reduce the effects of human activities contributing to landslide problem. The area around Murree is extremely fragile but little work has been done so far to evaluate the risks of erosion and mass movement. Major emphasis has so far been on the engineering base remedies, which have been partially successful but have limited scope. Major engineering work on various landslides has stabilized the movement for the time being but the enormous load added due to large-scale concrete work on the valley side has started showing adverse effects. Large cracks are developing in the retaining walls and most of the channels constructed for diversion of drainage water have been broken. New scarps are developing along major tension cracks on the hillside and movement has started along them. Engineering methods added with bioengineering techniques is considered effective to control soil erosion and mass movement, such as in the Kashmiri Bazar landslide area. Same techniques should be adopted at other landslide prone areas along with an efficient surface drainage and sewerage system.

There is also an urgent need to prepare comprehensive landuse and hazard maps not only for the Murree Town but also for the adjoining areas. This requires detailed study of the area over a longer period of time. No attention has been paid to most of the landslides located away from the main roads or highways. Large area is eroded along major steams in the area where people are forced to abandon their houses and valuable land due to landslides. Most of these landslides are not even marked on a proper map.

Summary

The geological structures in the area play an important role in the slope instability. Deformation associated with major faults such as MBT and its splays develop weak zones in strata, which ultimately lead to failure.

Study of selected major landslides demonstrates that the landslides in the Murree area are primarily triggered by the slope failure along the bedrock-colluvium interface mainly in response to excavation for road construction/widening. Once initiated, the escarpment progressively migrates upslope engulfing steep tension cracks. At this stage the landslides involve both the colluvium as well as the bedrock. Joint planes, both pre-existing as well as those related with the slope failure facilitate rock sliding leaving behind striations and slickensides on planar surfaces of the intact bedrock.

The Nergoli-Aliot-Dewal road section is highly unstable. This is mainly due to a relatively steeper slope, right from the Kashmiri Bazar Road down to Aliot. Although, it has a fairly thick vegetation cover but it should be avoided from rehabilitation as marked in the hazard map.

One of the crucial observations of this study is about reactivation of apparently stabilized old landslide zones. Excavation in these zones and unmanaged drainage causes these zones to commonly reactivate and trigger major new landslide mass-movement.

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