A regional level preliminary landslide susceptibility study of the upper Indus river basin

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Abstract
The major goal of this research was to explore low cost means by which large tracts of mountainous terrain (~75000 km²) can be screened for landslide-related hazards. For upper Indus watershed study, landslide susceptibility index maps were generated by coupling two main indicators groups: 1) environmental risk factors, which mainly contain slope angle, slope aspect, elevation, lithology maps; and 2) the causative factors, which include seismicity and rainfall. GIS based expert driven weighted overlay and fuzzy logic techniques were adopted to generate susceptibility maps for this preliminary landslide hazard study. The results obtained from this study were validated with landslide inventory mapping and other landslide historic data scattered throughout the upper Indus watershed. This kind of regional level landslide susceptibility mapping can play a vital role in identifying those areas where more detailed assessments of landslide hazards should be undertaken.

Keywords: Remote sensing, GIS, susceptibility mapping, fuzzy logic, Indus river.

Introduction
Landslide susceptibility is the probability of the spatial occurrence of a landslide or mass wasting event in a particular area, based on its prevalent geo-environmental settings [Brabb, 1984; Vandine et al., 2004]. Landslides are more likely to occur under similar geologic and geomorphologic conditions that have spawned past slope instability [Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Carrara et al., 1992; Carrara and Guzzetti, 1995; Hutchinson, 1995]. In other words, the causative factors which aggregatedly served to trigger landslides in any particular area should be collected and assessed to formulate predictive models empirically, statistically, or in a deterministic manner [Crozier, 1986; Hutchinson, 1988; Dietrich et al., 1995].

Various methods and procedures have been described in the literature those explain the basic
principles and techniques to evaluate landslide susceptibility and evaluate the hazards posed therein [Carrara, 1983; Hansen, 1984; Varnes and IAEG Commission on Landslides and other Mass-Movements, 1984; Crozier, 1986; van Westen et al., 1997; Glade et al., 2005]. It is rarely practical to apply all manner of methods and models adopted in the literature because the scale of the various efforts typically vary by several orders of magnitude, and such analyses depend upon the quality and resolution of available data, as well as financial resources. Based on a review of published literature [Hutchinson, 1995; van Westen et al., 1997; Guzzetti et al., 1999], the most common approaches for landslide susceptibility mapping fall into two broad categories: qualitative or quantitative, and direct or indirect methods. These can further be divided into four major groups, such as inferential, statistical, deterministic and heuristic, or index-based approaches [Verstappen, 1983; Nossin, 1989; Hansen, 1984; Varnes, 1984; Melody, 2004].

The inferential approach employs qualitative/subjective methods to construct landslide susceptibility maps, or direct methods, which focus on visual analyses of anomalous topographic expression, from the interpretation of aerial photographs or hill shade stitched topographic maps for small areas (<10,000 km²) [Verstappen, 1983; Nossin, 1989; Melody, 2004; Guzzetti et al., 2006]. Statistically based models are an indirect way to quantitatively assess landslide hazards. Most of the statistical approaches such as bivariate, multiple regression, and discriminant analysis [Brabb et al., 1978; Newman et al., 1978; Guzzetti et al., 1999; Cardinali et al., 2002; Ayalew and Yamagishi, 2005] have been applied to relatively small areas (<1:25,000) where the physical conditions are assumed to be similar [Melody, 2004; Schernthanner, 2005]. The Deterministic models are based on an understanding of the physical laws governing slope instability. Process based deterministic criteria generally utilize the quantitative theory of slope instability in a GIS environment using digital information (slope angle, slope aspect, , land cover, geology and vegetation cover) to delineate relative landslide potential across the small study areas provided that the geomorphic and geologic conditions and types of landslide are all similar [Melody, 2004].

Several methods and approaches are discussed early in this section to perform landslide susceptibility and hazard zoning maps. The larger the area, the less consistent or precise the baseline geoscience information generally becomes. Other decision factors include the quality, availability, or resolution of the landslide inventory, as well as baseline geoscience data sets in digital format, such as: surficial geology, bedrock geology, digital topography, etc. Each landslide susceptibility study focuses on the identification of those parameters or variables that generally control slope instability of a given area. We sought to identify controlling variables by gathering all the available geomorphological and environmental factor maps across the study area. The majority of research related to landslide susceptibility mapping is limited to small regions (<1:25,000). In regional studies where the extent of the area exceeds thousands of square kilometers, conditions may vary considerably. In regional scale studies, the level of detail and accuracy of the geologic and topographic maps and the digital elevation models tend to decrease with decreasing data resolution and increasing scale. The reliability of such products, therefore, becomes investigator-dependent. A few attempts have been made to compute landslide susceptibility and hazard assessment on a regional scale (>1:100,000). Significant contributions in this regard include the efforts performed by Nilsen and Brabb [1977], Brabb et al., [1978], Brabb, [1995], Hansen et al., [1995], Dai et al., [2002]. Expert driven qualitative Heuristic and semi-quantitative fuzzy logic techniques are often employed to obtain more reasonable results [Pradhan, 2010,
The heuristic/weighted overlay approach is an expert driven qualitative method for landslide susceptibility mapping, which is based on superimposition of qualitative map layers, such as: geologic, hydrologic, slope, land use, soil science maps, etc. [Erener and Uzgun, 2008; Bachri and Shresta, 2010; Intarawichian and Dasananda, 2010]. In this approach, the input map layers are usually different units and numerical systems with diverse ranges. In order to combine these in performing the analysis, each cell from each map layer must be reclassified into a common preference scale, such as 1 to 9, with 9 being the most favorable. In this manner, all of the contributing layers can be reclassified to bring them into a common scale of ranking. Since landslide trigger factors vary widely from one place to another, it is essential to incorporate the site-specific factors in some reasonable array, whereby some map layers exude greater tendency towards failure (landsliding) than others. The more significant triggers, like active faults causing earthquakes, are given more weightage than other factors [Pachauri and Pant, 1992].

Fuzzy logic is a relatively quick, straight forward, and inexpensive method recently developed as a GIS tool for regional scale landslide susceptibility mapping. It is a semi-quantitative technique that has been used by many researchers for landslide susceptibility on regional scale [e.g. Binaghi et al., 1998; Pistocchi et al., 2002; Saboya et al., 2005; Wang et al., 2008; Pradhan, 2010, 2011; Feizizadeh and Blaschke, 2011; Kayastha et al., 2013]. It was originally introduced by Zadeh [1965], and received considerable attention because it allowed multiple overlay analyses and multi-criteria decision making, which allows an unlimited number of dynamic variables to be considered, which is crucial in landslide studies because of the unique character of each study area. In landslide susceptibility mapping, fuzzy logic defines the instability factors as members of a set reaching from 1 (expressing the highest susceptibility) to 0 (expressing no susceptibility) of landsliding, and allows different degrees of membership therein, between these extremes. Two main steps are generally performed when applying fuzzy logic in ArcGIS; fuzzification (fuzzy membership process), and fuzzy overlay analysis. In fuzzification, input map layers are reclassified or transformed, while during the fuzzy overlay step, the fuzzified map layers are combined using several fuzzy operators, such as fuzzy operators (e.g. fuzzy AND, fuzzy OR, fuzzy algebraic sum, fuzzy algebraic product and fuzzy gamma).

Expert driven qualitative weighted overlay and semi-quantitative fuzzy logic techniques were utilized for this preliminary landslide susceptibility mapping at a scale of 1:100,000 for Upper Indus River basin with an area of 75000 km². The decision to split a landslide hazard map into different zones depends upon the size of the area, and is subjective in nature [Nilsen and Brabb, 1977; Brabb, 1984; Guzzetti et al., 2006]. For small scale regional level studies (> 1:100,000) the hazard classification boundaries can be defined subjectively, based on expert knowledge. These levels were normalized and split into percentages of the entire region for all the susceptibility maps: low hazard (0 - 25%), moderate hazard (26 - 45%), high hazard (46 -65%), and very high hazard (>65%) for both of the susceptibility methods used for this study: Weighted overlay index predictions and fuzzy logic.

This was the first regional level effort made of the study area because no previous studies had attempted to encompass more than small, project-specific areas. A few landslide hazard maps of modest scope and scale have been prepared along important transportation corridors, such as the Murree Kohala-Muzaffarabad Road and Azad Kashmir [Saeed and Malik 1990; Kamp et al., 2008; Peduzzi, 2010] and other portions of northern Pakistan [Calligaris et al., 2013]. Most of the upper Indus River Basin is bereft of any meaningful technical data.
because the region is inaccessible due to the severe terrain conditions, the absence of LiDAR imagery, lack of high quality aerial photography, and paucity of local expertise with respect to the identification of landslide-related geomorphic features. The results obtained from this study were validated with landslide inventory mapping [Ahmed and Rogers, 2014] as well as historic data obtained from more than 350 documented rockslides [Hewitt, 1982, 1998; Shroder, 1993; Shroder and Bishop, 1998; Korup et al., 2010; Hewitt et al., 2011], scattered throughout the Upper Indus watershed. The major objective of this study was to prepare a regional reconnaissance landslide susceptibility map of the upper Indus River Basin which can play a key role in identifying those areas where more detailed landslide hazard mapping might, or should be, undertaken in the future.

**Study area**
The main Indus River channel originates in the Tibetan Plateau, one of the planet’s greatest active erosional platforms [Korup et al., 2010]. The Indus River drainage system encompasses a very large catchment area and its tributaries tend to follow the longitudinal valleys in the steepest areas, then flow anomalously, cutting across the structural grain of the mountains until they join the main stem of the Indus River in northern Pakistan [Kazmi and Jan, 1997; Leland et al., 1998]. The main Indus River channel enters northern Pakistan from Jammu Kashmir, a territory in dispute between India and Pakistan, and flows through the Great Himalayan Ranges, finally merges with the Arabian Sea, 3,020 km downstream. The study area selected for landslide susceptibility mapping encompasses the upper Indus River Basin upstream of Tarbela Dam and Reservoir. It’s most distinguished tributaries in northern Pakistan include the Gilgit, Hunza, and Shyok Rivers, which contribute substantial flows into the main stream (Fig. 1).

![Figure 1 - Map of the Upper Indus River Basin, showing the principal tributaries upstream of Tarbela Dam in northern Pakistan. This area is outlined in red comprises approximately 75,000 km² and is shown in the index map at upper right.](image-url)
The upper Indus River Basin is a region of extremely rugged terrain where the Himalaya, Karakoram and Hindu Kush Mountains are being uplifted along an active tectonic boundary between the Indian and Eurasian Plates [Hewitt, 2009; Korup et al., 2010]. This area is perturbed by active thrust faults and mega shear zones including: the Main Boundary Thrust (MBT), the Main Karakorum Thrust (MKT), and the Main Mantle Thrust (MMT), enigmatic syntaxes, deep gorges and sutures marked by mélange belts of the Indus and Shyok sutures [Kazmi and Jan, 1997]. All these features are responsible for the high seismicity of the region, and frequent Magnitude 8+ earthquakes (1897, 1905, 1934 and 1950 were M~8) have been reported during the last two centuries [Yeats and Lillie, 1991]. The tectonically active Nanga Perbat and Haramosh Massif (NPHM) region is probably the most susceptible region to landslides because of a tectonically sheared strata, steep slopes, a high rate of bedrock incision (driven by tectonic uplift), and thick layers of colluvium mantling most of the slopes, which contain large boulders. This region lies in the central part of the Indus River, which is criss crossed by the MMT, a major tectonic boundary which is believed to be the extended part of the Indus Suture Zone in the Great Himalayan Range [Tahirkheli et al., 1979; Kazmi and Rana, 1982; Dipietro et al., 2000].

A regional geologic map of the region was published by the Geological Survey of Pakistan in 1993. This map includes a variety of geologic formations of vastly differing age exposed along the main stem of Indus River (Fig. 2). The chief rocks units exposed in the Indus River Basin are granitic in nature, and are believed to have formed in magmatic plutons and smaller bodies [Kazmi and Jan, 1997].

![Figure 2 - Geological Map of the study area [Geological Survey of Pakistan, 1993].](image-url)
These rocks dominant the exposures in Skardu, Nanga Parbat, Naran, Hazara, and Gilgit areas of northern Pakistan. The geologic units outcropped along the main Indus River channel in the Skardu Basin and nearby areas are Miocene to Cretaceous age rocks of the Kohistan-Ladakh Batholith and associated plutons (Tk\textsubscript{b} & Tk\textsubscript{m}). These units are mainly comprised of granites, granodiorites, quartz diorite, and hornblende gabbros. The formations comprising the lower elevation hills approaching Tarbela Dam also exhibit landslide hazards [Ahmed and Rogers, 2014]. These areas are underlain by Precambrian basement rocks (pCb), undifferentiated Precambrian age Metamorphic Rocks (pCs), mixed Precambrian metamorphic and sedimentary rocks of Tanawal formation (pCt), and the Salkhala formation (pEs) along the main stem of the Indus River.

The valley hills in the Indus River Basin exhibit an extensive amount of slope failures, large rockslide avalanches (volumes >10 km\textsuperscript{2}) and with a broad range of mass movement processes especially along the main Indus River channel [Shroder, 1993; Kazmi and Jan, 1997; Hewitt et al., 2011; Ahmed and Rogers, 2014]. The higher slopes and peaks are typically covered with glaciers, snow, and in the lower reaches of the valleys, alluvial fans and flood terraces are common features. Based on the landslide inventory mapping [Ahmed and Rogers, 2014], the geologic formations expressing substantial mass wasting features are the Precambrian Basement rocks (pCb) and metasedimentary rocks (MPzm) in the Nanga Perbat Haramosh Massif, and the regions underlain by undifferentiated Precambrian age Metamorphic Rocks (pCs), and mixed Precambrian metamorphic and sedimentary rocks (pCt). The most likely triggering factors for these events appears to have been adverse geologic structure, high seismicity associated with active thrust faults, and severe climatic conditions associated with the annual monsoons that impact the region. These variables combine to make the area more susceptible to large scale land slippage than any other in the world [Keefer, 1984].

**Data and material**

The most important step in constructing a landslide susceptibility map is the collection of indicator map units, then assigning their weighting and ranking with respect to their relative contributions to slope instability. Several ranking options are provided in the ArcGIS software which can easily be employed. The input map layers are usually different units and numerical systems with diverse ranges. In order to combine these in performing the analysis, each cell from each map layer must be reclassified into a common preference. For this analysis, the input map layers were reclassified using a ranking scale of 1 to 9. Each value class in every single input raster map was assigned a new, reclassified value; on an evaluation scale between 1 and 9, where 1 represents the lowest probability, and 9 the highest, for the landslide susceptibility analysis. The resulting reclassified map is a raster dataset wherein each cell corresponds to a value that equates to an anticipated risk that is based on expert knowledge input.

For this study, the landslide susceptibility index maps were generated by coupling two main indicator groups: 1) environmental risk factors; which contain slope angle, slope aspect, curvature, elevation, land cover/NDVI (Normalized Difference Vegetation Index), lithology, and distance to major rivers maps; and, 2) the causative factors: which include seismicity and rainfall with respect to the local terrain conditions. The slope angle, slope aspect, curvature and elevation maps were generated in ArcGIS 10 from ASTER DEMs.
data with a 30 m spatial resolution, which is suitable for regional studies [Kamp et al., 2008; Gullà et al., 2008]. For all of the environmental and causative factor maps, the weights were assigned linearly for each class of the respective map layer at a weighting scale of 1 to 9, where 1 is the least susceptible and 9 the most susceptible to landsliding.

**Lithology map layer**
The landslide susceptibility varies greatly with type of the rock units exposed in the respective study areas. The lithology of Upper Indus River watershed includes 25 lithological units identified in the regional geological map of northern Pakistan (1:1000,000 scale). This was digitized and rasterized by the authors from the original source file [Geological Survey of Pakistan, 1993].

![Figure 3 - Normalized relationship between the number of mapped landslides and the area of exposed geologic formations along the main stem of the Indus River.](image)

The given scale of the geological map is suitable for regional hazard studies employing a relative estimation of weights. Some studies of isolated areas suggests that the outcrops exposed in northern Pakistan are intensely sheared, folded, and faulted due to active tectonic processes [Hewitt, 1982, 1998; Shroder, 1993; Korup, 2010; Hewitt et al., 2011; Calligaris et al., 2013]. Landslide prone strata were outlined based on analysis of the regional level landslide inventory map along the Indus River [Ahmed and Rogers, 2014], the tectonic map, bedrock geology maps, and a map showing the distribution of more than 350 documented rockslides. These comparisons suggest that mass wasting appears to favor the bedrock units exhibiting the lowest shear strength (gneisses, phyllite, slate and shales) and the rock units which are severely fractured and perturbed by active tectonics, such as thrust faults and associated shear zones. The normalized relationship between the landslides and various geologic formation exposed along the Indus River are presented in Figure 3. The rock units with relatively week geologic strength (MPzs, Eat and JPzd) seem to have spawned a greater percentage of the mapped landslides per unit area (100 km²).
### Table 1 - Ranking of different geological formations.

| S. No | Geologic Formation                                      | Major Rocks Description                                                                 | Rating |
|-------|---------------------------------------------------------|-----------------------------------------------------------------------------------------|--------|
| 1     | Cb (Carboniferous Rocks)                               | Slates, phyllitic slates with subordinate limestone and quartzite                      | 7      |
| 2     | CDK (Carboniferous to Devon. Rocks)                    | Crinoidal Limestone, dolomite and partsing of slates                                   | 3      |
| 3     | Eat (Cambrian Rocks)                                   | Limestone, dolomite, sandstone shales, mudstone, conglomerate etc.                     | 8      |
| 4     | Eg (Cambrian Igneous Rocks)                            | Mostly Granite and finely foliated gneisses                                            | 3      |
| 5     | JK (Jurassic Rocks)                                    | Intensely deformed, banded amphibolites, hornblende, gabbros, diorite, garnet Schist.  | 5      |
| 6     | JPM (Jurassic To PermianMetasediments)                 | Marble and dolomitic marble, graphitic phyllitic and calcareous Schist                 | 5      |
| 7     | JPzd (Jurassic to Paleozoic Rocks)                     | Slate, phyllite, gneiss, quartzite, limestone and marble.                              | 5      |
| 8     | KJc (Cretaceous to Jurassic Rocks (Chilas))            | Norite, Pyroxene-gabbros, dunite and peridotites                                      | 3      |
| 9     | KJCy (Cretaceous to Jurassic)                          | Volcanoclast sediments metamorphosed green schist, interbedded slates.                | 6      |
| 10    | MPzm Mesozoic to Paleozoic(Metasedimentary Rocks)      | Sandstone, shale quartzite, limestone, slates, phyllite.                               | 8      |
| 11    | MPzs (Meso to Paleozoic Rocks)                         | Volcanic rocks, limestone, red shale, sandstone, quartzite, conglomerate.              | 5      |
| 12    | Mz(Mesozoic Rocks)                                     | Fossiliferous Limestone, shale, marl and sandstone etc.                                | 5      |
| 13    | PCa (Permian to Carboniferous Igneous Rocks)           | Alkaline and tourmaline Granite, Syenite with miner carbonates.                       | 2      |
| 14    | PVCb n PEb (Pre-Cambrian basement Rocks)               | Feldspathic Gneiss, graphitic schist, quartzite and marble intruded with granite, diorite | 6      |
| 15    | PEM (Pre-Cambrian low grade Metasedimentary Rocks)     | Slates, quartzose sandstone, phyllite, algal limestone, quartzite units                | 5      |
| 16    | PEs (Precambrian Metamorphic Rocks)                    | Schistose to Phyllitic quartzite, schist, slate marble                                 | 4      |
| 17    | PEt (Pre-Cambrian Metamorphic and Sed. Rocks)          | Metaquartzite, Garnet mica schist.                                                    | 5      |
| 18    | Ps-Pg (Permian Rocks)                                  | Dolomite, Fossiliferous limestone and shale sandstone                                  | 4      |
| 19    | Pzm (Paleozoic Rocks)                                  | Slate, phyllite and quartzite with gabbro, diorite and granite intrusions             | 3      |
| 20    | Q1(surficial Deposits)                                 | Clays, silt, sands and gravels                                                         | 1      |
| 21    | TKb (Miocene to cretaceous, batholith and pluttons)    | Granite, granodiorites, hornblende gabbros etc                                        | 2      |
| 22    | TKk (Miocene to cretaceous, batholith and pluttons)    | granite, granodiorites, diorite and granitic gniess etc                               | 2      |
| 23    | Tkm( Mafic n felsic)                                   | Younger tertiary Gabbros, diorite and granite and pegmatites                          | 3      |
| 24    | KJD (Dras Volcanic Rocks)                              | Basalt, andesite and pillow lawa.                                                     | 5      |
| 25    | CPEm (Carboniferous to Pre-Cambrian Metasedimentary and Sedimentary Rocks) | Schist, phyllite, marbles, quartzite, dolomite, limestone slate                   | 6      |
Ranking of the mapped bedrock units were assigned linearly, on a scale 1 to 9, with respect to the above analysis and their corresponding geologic strength (the type of rock and their anticipating engineering behavior were based on expert judgment) (Tab. 1).

**Elevation map layer**

Surface relief is one of the important conditioning factors affecting landslides which influence the dominant geomorphic processes, especially in the rugged mountain ranges. An elevation map was extracted from the ASTER DEM 30m resolution data (Plate-1(a)). To increase the utility of this map layer for landslide susceptibility mapping, the landslide inventory map and documented rockslides were overlaid onto the elevation map (Appendix-1). This overlay revealed that 64% of the mapped landslides were likely triggered in elevation range 2000-4000 m and 24% occurred in the elevation range of 1000-2000 (Fig. 4). This analysis assisted in the ranking of elevation zones according to the anticipated landslide hazard for susceptibility analysis on a linear scale of 1-9 (Tab. 2(i)). The rankings drop slightly with increasing elevation because of increased glacial cover.

![Figure 4 - Histograms showing the relationship between the number of landslides with respect to different elevation zones.](image)

**Slope map layer**

Slope angle/inclination is the single most important parameter that influences slope failure mechanisms. In landslide susceptibility analyses the highest ranking is generally given to slope angle/inclination [Pradhan, 2011; Kayastha et al., 2013]. The slope map was also extracted from ASTER DEM of 30m resolution. The maximum slope angle in the study area was found to be 86°. Figure 5 shows the comparison of overlapped landslides with different slope angles in the NPHM. The analysis of the landslide inventory map and documented rockslides suggests that areas underlain by slopes between 30° and 45° exhibit the greatest number of slope failures (44%), while the slopes inclined less than 15 degrees exhibited the least slope failures (Fig. 5). The slope inclination map was distributed into five main classes (Plate-1(b)). These slope inclination classes were ranked linearly, increasing from
0 to 45 degrees, and then decreasing for steeper slope angles, on a rating scale from 1 to 9 (Tab 2(ii)). In this case the ratings are influenced by the observed distribution of mapped landslides, shown in appendix-2. The effect of rockfalls was not considered in the regional approach, even though it is generally associated with the steeper slopes in the higher elevations (>3000 m) terrain but limited to small areas.

![Figure 5 - These histograms illustrate the relationship between slope angle zones with identified landslides in the upper Indus River Basin.](image)

**Slope aspect map layer**

The slope aspect map is the reflection of solar insolation [Calligaris et al., 2013], wind direction, intensity of rainfall [Tarolli et al., 2011; Liu and Shih, 2013], and favors erosion of those slopes facing the sun. This factor is responsible for asymmetric deterioration and disintegration of slope surfaces, so it was subdivided into eight classes, each of which contains a 45° radius sector (Plate 1 (c)). The landslide inventory maps were overlapped on the aspect map generated from the ASTER DEM 30m resolution (Appendix-3). This analysis reveals that the landslides are not concentrated along any particular azimuth quadrant (Fig. 6). Different aspect directions exhibit different landslide densities. Initially, the comparison was made by dividing aspect into eight equal interval classes and number of landslides was counted in each prevailing directions. The literature review [Melody, 2004; Rashid, 2004] suggests that the predominant southwest-to-southeast azimuth of seasonal Monsoon rainfall exerts more impact on the slopes facing south to northwest (between azimuths 180 and 315). The hill slopes facing southwest are most susceptible to landsliding (~45%) and, secondly, those facing northwest. Based on the literature describing the seasonal wind driven Monsoon rainfall and analysis of the study area, the aspect directions were weighted accordingly. Using a 1 to 9 rating scale (Tab. 2(iii)), the higher weights were assigned to those azimuths which appear to be more susceptible to mass wasting processes (southwest, west and northwest), because the increased volume of runoff correlates with increased erosion, while lower runoff is associated with lower rates of denudation and erosion [Ruff and Czurda, 2008].
Curvature map layer
Curvature is another geomorphic indicator of topographic features [Lee et al., 2003], which is defined as rate of change of slope gradient in a particular direction. It is related to the flow pattern on a slope at particular locations [Rogers, 1997; Kayastha et al., 2013]. It affects surficial erosion by converging or diverging the flow of runoff down the slope [Lee et al., 2003; Pradhan, 2010]. Slope curvature exhibits two extreme values having positive and negative values. A positive value generally represents a surface that is convex upward at particular location while the negative values describe surfaces that are concave upward. Zero to lower positive and lower negative numbers (small absolute values) describe flat lying areas. The literature review indicates that higher the negative value, the more probable that landslides will occur. A flat surface has the lowest probability of triggering landsides. There is a strong relationship between the slope curvature with higher concavity values (-ve). In a typical rainfall event slopes with concave upward surfaces will tend to retain more water, hence, there is more time for water to infiltrate into the slopes and thereby exert a greater probability of triggering landsides [Lee et al., 2003]. For the upwardly convex sloping faces, the condition will be the opposite of concave slopes. For the study area the plan curvature map was extracted from the DEM data using ArcGIS 10 software (Plate 1 (d)). The range of curvature values were divided into six classes and assigned weights accordingly, with respect to landslide susceptibility risk (Tab. 2(iv)).

Seismic hazard map layer
Previous studies of the Hindu Kush-Greater Himalaya ranges have identified seismicity and rainfall as the principal factors triggering landslides [Keefer, 1984; Korup, 2010; Hewitt et al., 2011]. Seismicity is the main triggering factor for mega rockslides, based on historic records [Keefer, 1984] and landslide inventory mapping results [Ahmed and Rogers, 2014]. The rasterized Seismic Hazard Map (1:1000,000) of the Upper Indus River Basin was prepared by using data from the Geological Survey of Pakistan [Giardini et al., 1999], which weights the relative hazards by dividing peak ground acceleration (PGA) data by acceleration due to gravity (Plate 1 (e)). The
relative ranking of the different levels of seismic hazards are listed in Table 2(v).

**Structure map layer**
The most likely triggering factor for large rockslope failures in the study area is the high seismicity associated with a number of active thrust faults and smaller associated faults [Keefer, 1984]. Whether or not a fault is tectonically active, they can be regarded as significant zones of weakness within the geologic units they traverse. Faults and shear zones also preferentially bound and restrict the flow of groundwater, influencing slope stability [Pourghasemi et al., 2012]. Plate 1(f) shows a tectonic structure map which highlights the locations of major thrust faults extracted from the Tectonic Map of Pakistan [Kazmi and Rana, 1982]. The smaller faults include those either extracted from the geologic map or mapped directly by observing their impressions on the hillshade map of the study area. All these faults were then buffered in different zones with respect to their posed seismic hazard to account for their contribution in the landslide susceptibility analysis and ranked accordingly (Tab. 2(vi)). The major concentration of landslide appears to be associated with either the main Indus River tributaries where these are crossed or intercepted by recognized faults.

**Rainfall map layer**
Rainfall likely plays a more significant role in triggering mega slides, but on a less frequent basis than earthquakes. Monsoon rainfall originating from the Bay of Bengal and the North Arabian Sea enters Pakistan along a southwesterly to northeasterly azimuth [Melody, 2004; Rashid, 2004]. This rainfall season is limited to about three months and commonly engenders intense precipitation and flash flooding. Pakistan typically receives between 65 and 70% of its cumulative annual rainfall during the Monsoon. The high altitude climes of northern Pakistan lie within a semi-arid zone that doesn’t receive much of the Monsoon precipitation. Note how the aridity of the higher elevations (0-50 mm/yr) impacts about 35% of the study area (see Plate 1(g)). The more pronounced impact of Monsoon rainfall is usually felt in the lower elevations of the study area (Abbottabad, Mansehra, Peshawar, etc.), where the landsliding is the most frequent geo-hazard during the wet summer months because of intense rainfall of short duration. Monsoon monthly average rainfall raster data (mid-June to mid-September) was obtained from an open source available online [www.worldclim.org], gleaned from records collected between 1950 and 2000. Table 2(vii) shows the ranking of different rainfall zones with respect to their anticipated susceptibility hazards.

**Drainage map layer**
Stream channels significantly impact fluvial processes and bedrock incision in tectonically active mountain ranges. The river’s longitudinal profile is highly irregular and fragmented because of the large slope failures along the river [Ahmed and Rogers, 2014]. The distance from major perennial channel also plays an active role in assessing landslide susceptibility hazards. Appendix 4 shows the overlapped landslide maps on the upper Indus River drainage map, from which the maximum concentration of slides along the main river channel and its associated tributaries. To incorporate the impact of drainage on the adjacent slopes, different buffer distances extending outward from the major channels were generated in the ArcGIS10 software (Plate 1 (h)). Different weights were then assigned along the main stem of the Indus River watershed and along the principal tributaries (Tab. 2(viii)).
**NDVI map layer**

The NDVI map was extracted from Landsat TM5 satellite imagery (collected between 2008 and 2011) of the Monsoon rainfall season (mid-June to mid-September) downloaded from an open source website [http://earthexplorer.usgs.gov](http://earthexplorer.usgs.gov). This data was then divided into three major classes: densely vegetated, slightly vegetated, and bare soil/rock areas (Plate 1 (i)). The literature suggests that the soil/rock bereft of vegetation cover is more prone to erosion and landsliding because of the maximum exposure to weathering agents [Erener and Uzgun, 2008; Intarawichian and Dasananda, 2010]. Table 2(ix) presents the relative ranking of the different NDVI values with respect to their anticipated risk.

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**Plate 1 - Map layers used for landslide susceptibility mapping in the Upper Indus River Basin,**

(a) Elevation map layer, extracted from ASTER DEM data showing ranges of elevation in meters (b) Slope Map extracted from ASTER DEM data, (c) Slope Aspect Map extracted from ASTER DEM data, (d) Curvature map layer, extracted from ASTER DEM data, (e) Rasterized Seismic Hazard Map [Giardini et al., 1999], (f) Rasterized Structure Map [Kazmi and Rana, 1982], (g) Average Monsoon Rainfall Map, (h) Drainage Map extracted from ASTER DEM data, (i) NDVI Map extracted from Landsat TM5 satellite imagery (collected between 2008 and 2011 of the Monsoon rainfall season (mid-June to mid-September)).
The Upper Indus River Basin also supports one of the largest alpine glacier systems (Batura Glaciers near Hunza and the Biafo glaciers in the Karakorum Range) in the world [Hewitt et al., 1989; Wake, 1989; Tahir et al., 2011]. These alpine glaciers are rapidly retreating so the effect of glaciation in the region was not considered in the final hazard assessment and those areas covered by glaciers were masked out of our analyses using a shapefile. An ESRI shapefile showing these glaciers was extracted from the Geologic Map of Pakistan (which defines the areal extent of the glaciers at scale of 1:1,000,000 between 1988-92). The impact of rapid glacial retreat in the higher elevations on landslides and rockslides needs to be assessed, but was beyond the scope of this study because of the paucity of remotely sensed imagery.

Table 2 - Ranking of environmental and triggering factor map layers used in the landslide susceptibility analysis.

| i- Elevation (m) | ii- Slope (degrees) | iii- Aspect (degrees) | iv- Curvature |
|------------------|---------------------|----------------------|--------------|
| Classes Rating   | Classes Rating      | Classes Rating       | Classes Rating |
| 0-1000 2         | 0-15 2              | 0-45 (NE) 2         | -145 to (-4) 9 |
| 1000-2000 5      | 15-30 4             | 90 (E) 4            | -4 to (-1) 8  |
| 2000-3000 6      | 30-45 8             | 135 (SE) 6          | -1 to (0) 3   |
| 3000-4000 8      | 45-55 6             | 180 (S) 8           | 0 to 1 2      |
| 4000-5000 7      | >55 5               | 225 (SW) 9          | 1 to 3 4      |
| 5000-6000 6      |                      | 270 (W) 9           | 3-147 5       |
| 6000-7000 5      |                      | 315 (NW) 8          | 360 (N) 3     |

| v- Seismic hazard | vi- Structure |
|-------------------|---------------|
| Minor to no damage| g value       |
| <0.05             | Rating 3      |
| Minor to moderate damage | 0.05 to 0.1 | 5 |
| Medium to severe damage | 0.1 to 0.3 | 7 |
| severe damage     | >0.3          |

| vii- Precipitation | viii- Drainage |
|---------------------|----------------|
| Rainfall zones      | Indus River    |
| Zone 1 0-50 2      | Buffer Zones (m) Rating |
| Zone 2 50-100 3    | 0 – 1000 9     |
| Zone 3 100-150 3   | 1000 – 2500 6  |
| Zone 4 150-200 4   | 2500 – 5000 4  |
| Zone 5 200-250 5   |                  |
| Zone 6 250-300 6   |                  |
| Zone 7 300-400 7   |                  |
| Zone 8 400-500 7   |                  |
| Zone 9 500-600 8   |                  |
| Zone 10 600-700 9  |                  |

| ix- NDVI |
|----------|
| Classes Value Rating |
| Bare Soil/Rock 0.025 to 0.1 7 |
| Less dense 0.1 to 0.3 5 |
| More dense 0.3 to 0.7 3 |
Results and Discussions
The choice of methods for a regional landslide susceptibility study is influenced by the size of the study area [van Westen et al., 1997]. Two approaches were employed for this regional level study so their results could be compared: weighted overlay (qualitative index based) and semi quantitative fuzzy logic. One of the principal assumptions employed in the susceptibility mapping analyses was that the causative factors triggering future landslides will be the same factors that have influenced landslides in the recent geologic past, influenced by the local terrain. To perform the susceptibility analysis, the rasterized form of the same layer factors described above were employed using ArcGIS10. All this information aided in the construction of landslide susceptibility maps as end products to describe different levels of susceptibility for different areas.

Weighted overlay technique and landslide susceptibility mapping
The heuristic/weighted overlay method is a simple, direct, and adequate methodology for evaluations of large land areas. Being qualitative in nature, the heuristic method is most often used for regional level studies seeking to construct reconnaissance level susceptibility maps [Erener and Uzgun, 2008; Bachri and Shresta, 2010; Intarawichian and Dasananda, 2010]. This GIS technique is largely based on rescaling of retrievable geo-data to a common scale, and the diverse input of raster, vectors and/or measured data, which is then rasterized and integrated for susceptibility or suitability analyses. The reliability of this qualitative method depends upon the investigator’s understanding of the operative geomorphic and/or environmental processes influencing a particular region.

For this study, the landslide susceptibility index maps were generated by coupling two main indicator groups: 1) environmental factors, which include slope, slope aspect, relief, land cover/NDVI, lithology, distance to active faults, and distance to major rivers; and, 2) causative factors, which include seismicity and rainfall. The reclassified factors (map layers) triggering slope instability were assigned weights between 0.0 and 1.0 which collectively add to 1.0 (or 100%), based on the relative importance to slope instability in the study area. In the Upper Indus River Basin, the major causative factors for deep seated landslides are thought to be high seismicity, intense precipitation brought on by seasonal Monsoons, and locally rapid snowmelt. A sensitivity analysis was applied to observe the significance of each individual factor for the susceptibility mapping and to obtain meaningful results. Each layer was multiplied by different weights, depending upon their anticipated contribution to triggering landslides in the study area. Several differently weighted overlay index susceptibility maps were generated by assigning different weights to the various map layers. Some of them are summarized in Table 3. Figures 7, 8, and 9 show a few of the resultant maps generated from running different weighting combinations. An ESRI shapefile showing the extent of glaciers in the study area was overlapped on these final preliminary regional level susceptibility maps in order to exclude these regions. A few of the combinations of differently weighted layer maps used for the susceptibility mapping and their respective results are summarized in Table 4.

In the first Run (#1 in Tab. 3) of equally weighted overlay index landslide susceptibility mapping, all the map layers were given same weight (10% each layer weight) using rainfall and aspect map layers separately weighted (Fig. 7).
Table 3 - Various combinations of map layers (in percentages) used for the weighted overlay Landslide Susceptibility Index mapping.

| Run | Relief | Slope | Curvature | Aspect | Rain | Seismic Hazard | Faults | Drainage | NDVI | Geology |
|-----|--------|-------|-----------|--------|------|----------------|--------|-----------|------|---------|
| 1   | 10     | 10    | 10        | 10     | 10   | 10             | 10     | 10        | 10   | 10      |
| 2   | 05     | 25    | 05        | 05     | 10   | 10             | 10     | 10        | 10   | 05      |
| 3   | 05     | 20    | 05        | 10     | 05   | 10             | 15     | 10        | 05   | 15      |
| 4   | 05     | 20    | 05        | 05     | 10   | 05             | 20     | 10        | 05   | 15      |
| 5   | 05     | 15    | 05        | 05     | 05   | 10             | 25     | 10        | 05   | 15      |
| 6   | 05     | 20    | 05        | 10     | 05   | 15             | 05     | 20        | 05   | 10      |
| 7   | 05     | 15    | 05        | 10     | 10   | 10             | 20     | 10        | 05   | 10      |
| 8   | 10     | 15    | 05        | 15     | 15   | 10             | 10     | 05        | 10   | 10      |

Table 4 show resultant variation in the results obtained from several combinations given in Table 3. In all of the weighted overlay-based susceptibility maps, the areas exhibiting ‘high’ to ‘very high’ hazards tend to be concentrated in those regions where more than three landslide triggering risk factors are dominant. Examples of very high hazards areas include the NHPM area, Skardu Basin, upper Gilgit and Hunza tributaries (location of major thrust faults, geology, slope and drainage are the major risk factors) and in the lower Indus River area near Dasu, where major thrusts, geology, drainage, and high Monsoon rains are the dominant risk factors.

Figure 7 - Landslide Susceptibility Map derived from equally weighted combination of map layers (Run 1). Zones delineating different levels of susceptibility were obtained by overlapping controlling factor layer maps and dividing these into four main groups, according to their respective level of hazard.
Figure 8 - Differently weighted overlay index landslide susceptibility map generated by applying the map layer rankings cited in Table 3 (Run 2).

Figure 9 - Differently weighted overlay index landslide susceptibility map generated by applying the map layer rankings cited in Table 3 (Run 4).
Table 4 - Variation in distribution of the landslide susceptibility hazards zones (in percentages) depending weighted combinations of different map layers

| Combination | Low Hazard | Moderate Hazard | High Hazard | Very High Hazard |
|-------------|------------|-----------------|-------------|-----------------|
| Run 1       | 20.3       | 48              | 22.7        | 9               |
| Run 2       | 19.3       | 44.2            | 24.4        | 12.1            |
| Run 3       | 20.1       | 37.2            | 28.1        | 14.6            |
| Run 4       | 23.1       | 32.4            | 29.2        | 15.3            |
| Run 5       | 18.8       | 30.1            | 32.5        | 18.6            |
| Run 6       | 22.4       | 39.6            | 27.2        | 11.8            |
| Run 7       | 24.7       | 41.2            | 23.0        | 11.1            |
| Run 8       | 24.4       | 43.9            | 20.4        | 11.3            |

Fuzzy logic technique and landslide susceptibility mapping

Fuzzy logic is commonly employed to deal with variables or components with undefined boundaries. Unlike weighted overlays, fuzzy logic is not a function which determines if a member or variable is “in” or “out” of a particular ranking; it defines the possibility, not the probability of an element, being a member of a set (or class), or not. The idea behind the fuzzy logic method is to consider all spatial objects on a map as members of a “set” [Zadeh, 1965]. In this overlay analysis, the weighting of individual layers is not appropriate because fuzzy logic is based on set theory, which is used to determine whether a particular location/member belongs to one or multiple sets (commonly represented as map layers). In other words, increasing or decreasing the weight of each layer factor does not increase the possibility of one location belonging to one class or a combination of multiple classes (sets). In landslide susceptibility mapping fuzzy logic defines the instability factors as members of a set reaching from 1 (expressing the highest susceptibility) to 0 (expressing no susceptibility) of landsliding, and allows different degrees of membership therein between these extremes. The initial fuzzy memberships were assigned subjectively to the reclassified map layers (Tab. 1) based on expert knowledge. After assigning fuzzy membership functions for each data layer, the input maps can be combined using one or a variety of fuzzy operators in intermediate stages, such as fuzzy operators (fuzzy AND, fuzzy OR, fuzzy algebraic sum, fuzzy algebraic product and fuzzy gamma). These operators are briefly defined as under.

Fuzzy operators

i-Fuzzy AND

This fuzzy operator is based on classical set theory, with values of 1 and 0. It can be defined by the following function:

\[ u_{(x)} = \text{Min}(u_A, u_B, u_c, \ldots) \quad [1] \]

Where \( u_{(x)} \) represents the degree of membership of \( x \) in a particular map layer (varying between 1 and 0), \( u_A \) is the membership value of map layer A at a particular location. Similarly, \( u_B \) is the membership value at a particular location of map layer B, and so on. According to this function, the output map layer value will be controlled by smallest membership value for a particular location. That can sometimes undermine the importance...
of a significant triggering factor (possibly shown on a map layer). For example, for two map layers with membership values of 0.6 and 0.3, the controlling value will be 0.3.

**ii- Fuzzy OR**

This fuzzy operator is based on Boolean OR logic union function, which is defined by the following expression:

\[ u(x) = \text{Max}(u_A, u_B, u_C, \ldots) \]  \[2\]

According to this function, the output map layer value will be controlled by largest membership value for a particular location. For example, for two map layers with membership values of 0.6 and 0.3, the controlling value would be 0.6.

**iii- Fuzzy Algebraic Product**

Fuzzy algebraic product function can be expressed by the following equation:

\[ u(x) = \prod_{i=1}^{n} u_i \]  \[3\]

Where \( u_i \) is the membership value of the \( i \)th map layer at a particular location, and \( i = 1, 2, 3, \ldots n \) corresponding to the number of maps to be multiplied. This fuzzy operator is decreasive in nature because of the multiplication of each map layer membership value is less than 1. The resultant value of the membership function at a particular location will be lower than, or equal to, the smallest causative map layer value. For example, for two map layers with membership values of 0.6 and 0.3, the fuzzy algebraic product is \( 0.6 \times 0.3 = 0.18 \).

**iv- Fuzzy Algebraic Sum**

Fuzzy algebraic sum is opposite to fuzzy product operator and can be expressed by the following equation:

\[ u(x) = 1 - \prod_{i=1}^{n} (1 - u_i) \]  \[4\]

This fuzzy operator is increasive in nature because of the combined effect of the contributing layers of each map. The resultant value determined by this function at a particular location will always be larger than from the largest causative map layer value. For example, for two map layers with membership values of 0.6 and 0.3, the fuzzy algebraic sum is \( 1 - (1 - 0.6) \times (1 - 0.3) = 0.72 \).

**v- Fuzzy Gamma**

Fuzzy gamma is a moderator between two fuzzy operators, and mediates the increasing trends of the fuzzy algebraic sum and the lowering impact of the fuzzy algebraic product.
Gamma values given for this fuzzy overlay combination tend to influence the distribution of different hazard levels in landslide susceptibility maps [Ghosh et al., 2012]. It is expressed by the equation:

\[
 u(x) = \left( \prod_{i=1}^{n} u_i \right)^\gamma \cdot \left( 1 - \prod_{i=1}^{n} (1 - u_i) \right)^{1-\gamma} \tag{5}
\]

Different landslide susceptibility scenarios can be analyzed using different gamma values. When \( \gamma \) approaches 1, the combination approaches the fuzzy algebraic product, and when \( \gamma \) approaches 0, the combination approaches the fuzzy algebraic sum. This operator is more suitable for regional level landslide susceptibility mapping [Saboya et al., 2005; Wang et al., 2008; Pradhan, 2011; Feizizadeh and Blaschke, 2011; Kayastha et al., 2013]. The major advantage of the fuzzy logic approach is the effective transformation of expert knowledge into fuzzy membership degree functions for susceptibility analyses.

In this analysis fuzzy gamma \( (\gamma) \) was used, which is more convenient method to perform the landslide susceptibility analysis [Wang et al., 2008; Pradhan, 2011; Feizizadeh and Blaschke, 2011; Sharifi et al., 2011; Kayastha et al., 2013]. The fuzzy algebraic sum and the fuzzy algebraic product were first calculated and then combined using the fuzzy gamma operator for the final susceptibility map, excluding the area under glaciers. Fuzzy gamma is a moderator between two fuzzy operators and mediates the increasing trends of the fuzzy algebraic sum and the lowering impact of the fuzzy algebraic product. Gamma values for this fuzzy overlay combination tend to control the distribution of different hazards in the susceptibility maps [Wang et al., 2008; Ghosh et al., 2012]. Different landslide susceptibility scenarios can be analyzed using different gamma values. When \( \gamma \) approaches 1, the combination becomes same as of the fuzzy algebraic sum, and when gamma approaches 0, the combination becomes equal to the fuzzy algebraic product.

Several gamma values were also considered, ranging from 0 to 1, with a linear rise of 0.1 in each susceptibility map. The most reasonable results can be achieved using a more realistic spread of susceptibility zones when \( \gamma \sim 0.90 \) [Pradhan 2011; Ghosh et al., 2012]. Figure 10 show the landslide susceptibility map generated using the fuzzy logic method (using \( \gamma = 0.90 \)). The map shows high to very high susceptibility values in those areas where the combined impacts of tectonics (active thrust faults), seismic hazards, and lithology are significant.

Both qualitative heuristic/weighted overlay and fuzzy logic susceptibility maps exhibited fairly similar distributions of susceptibility zones, especially the ‘high susceptibility’ zone. The final results obtained from both of the susceptibility mapping approaches show high to very high susceptibility values hazards tend to be concentrated in those regions where more than three landslide triggering risk factors are dominant. Examples of very high hazards areas include the NHPM area, Skardu Basin, upper Gilgit and Hunza tributaries (where major thrust faults, bedrock geology, slope inclination, and drainage are the major risk factors) and in the lower Indus River area near Dasu, where major thrusts, bedrock geology, drainage, and severe monsoon rains are the dominant risk factors.

In the heuristic weighted overlay index technique we manually assigned different weights with respect to their anticipated susceptibility level. Unlike weighted overlays, fuzzy logic is not a function which determines if a member or variable is “in” or “out” of a particular
ranking; it defines the possibility, not the probability of an element, being a member of a set (or class), or not. The fuzzy logic technique appears to elicit more realistic results than the weighted overlay techniques in that it provides a more precise distribution of the various possible hazard zones.

![Figure 10 - Landslide Susceptibility Map compiled by employing the Fuzzy Logic approach and excluding areas covered by alpine glaciers.](image)

**Verification of results**

Knowing the characteristics of a landslide catalogue, including completeness, sources and methods used to compile the information, is important because the actual record of landslides is crucial to estimate landslide susceptibility, hazard, or risk. An accepted constraint for these hazard maps was the relative scarcity of available data for this region. Despite the recognition of landslides pose the greatest short-term risk to engineered infrastructure in the region, the local authorities have yet been unable to address landslide susceptibility on a regional basis. The landslide inventory map and other documented rockslide location shapefiles were overlapped on this regional susceptibility map in order to ascertain its degree of reliability and to check the spatial agreement of past landslippage with the predicted landslide susceptibility zones.

The overall comparison shows more than 85% of the landslide locations matched with the hazard zones with having high to very high landslide susceptibility (Fig. 11). Greater concentrations of mapped landslides are observed in the tectonically active Nanga Perbat Haramosh region (high to very high hazard area because of the presence of MMT, MKT and other small active thrust fault systems in the area) shown in Figure 12.
Figure 11 - Landslide Susceptibility Map created using the Fuzzy Logic approach, combined with the landslide inventory mapping [Ahmed and Rogers, 2014] along the main stem of the Indus River. Green and red circles denote locations of dated and documented rockslides, respectively.

Figure 12 - Enlarged portion of the Landslide Susceptibility Map showing NHPM region (created using the Fuzzy Logic approach) combined with the landslide inventory mapping.
Figure 13 - Enlarged portion of the landslide susceptibility map prepared using the Fuzzy Logic approach, combined with the landslide inventory mapping in the Skardu Basin (Indus River flowing from southeast to the northwest in this view).

Figure 13 shows the landslide susceptibility hazard zones with overlapped mapped and documents rockslides in the Skardu Basin. These predictions appear to be contingent on the quality of the available input data. Both methods employed for this study were simple and reasonable to produce reconnaissance level hazard maps, which may be updated and improved by conducting more detailed field surveys and entering new data as it becomes available. This sort of regional effort is a necessary first step in developing countries so that follow-on, site-specific investigations will be encouraged and expected during feasibility planning for infrastructure projects.

Conclusions
Regional scale studies are generally limited in scope because of the coarseness, or low resolution, of the available data. An accepted constraint for these hazard maps was the relative scarcity of available data for this region, because no previous studies have been carried out to address regional landslide hazards. The present research emphasized the importance of landslide susceptibility mapping for regional level studies (75,000 km²) based on relatively simple, yet reliable, procedures. These products are intended to serve as “guide maps” to trigger more detailed project-specific analysis of particular sites in the region. Two approaches were employed for this purpose so that their results could be compared: heuristic/weighted overlay and fuzzy logic. The results obtained from both of the susceptibility mapping approaches show high to very high susceptibility hazard zones tend to be concentrated in those regions where more than three landslide triggering risk factors
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are dominant. Examples of very high hazards areas include the NHPM area, Skardu Basin, upper Gilgit and Hunza tributaries (where major thrust faults, geology, slope inclination, and drainage are the major risk factors) and in the lower Indus River area near Dasu, where major thrusts, geology, drainage, and heavy monsoon rains are the dominant risk factors. Each of these exhibited fairly similar distributions of susceptibility zones, especially ‘high susceptibility.’ Most of identified landslide features (more than 85%) in the inventory mapping and the documented rockslides locations overlap the most susceptible areas, based on the results of this subsequent landslide susceptibility mapping. This is encouraging for an initial reconnaissance level study. Keeping in view the limitations and uncertainties dictated by the limited information for this complex region, this end product possesses considerable uncertainty in precisely delineating various hazard zones. It would be rated as a regional reconnaissance level hazard map that is solely intended for planning purposes, the greatest value of which would be in highlighting those local areas worthy of more detailed site-specific investigation.

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Appendices

Appendix 1 - Enlarged view of the NHPM area, showing the mapped (yellow) and documented landslides (blue dots) on the elevation map.
Appendix 2 - Distribution of identified slope failures (the red dots and all of the mapped landslides outlined in dark grey) with the slope angles in the NHPM area.

Appendix 3 - Enlarged view of the NHPM area showing the relative concentration of landslides with respect to different aspect azimuths, between 0 and 360 degrees.
Appendix 4 - Mapped and documented landslides overlapped on the drainage map of the upper Indus River Basin.

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