Quantifying the Influences of Land Use and Rainfall Dynamics on Probable Flood Hazard Zoning

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Received: 08-12-2022, Received in revised form: 10-05-2023, Accepted: 28-06-2023, Published: 30-06-2023

Abstract

Flooding is Pakistan's most common natural hazard, and it is exacerbated by increased rainfall and urbanization. Khyber Pakhtunkhwa (KPK), Pakistan flood-prone zones were determined by superimposing six flood parameters in an ArcGIS 10.1 environment: Elevation, Buffers from rivers, rainfall, land use, slope and soil abbreviated as “EBRLSS”. Cellular automata based on artificial neural network (CA-ANN) along QGIS plugin module of Land Use Change Simulations (MOLUSCE) was used for predicting year 2050 land use, with a kappa value of 0.83. The results indicated that of the 75775 sq.km land area covered by this research region, 3.37% (2553.62 Km^2) falls in extremely high risk, 18.44% (13972.91Km^2) falls in high risk, 11.26% (8532.27 Km^2) falls in moderate risk, 0.51% (386.45 Km^2) falls in low risk, and just 66.42% (50329.76 Km^2) falls in very low risk areas. In KPK, like in any other place, a multi-criteria flood risk-vulnerability assessment is consequently necessary for preparation and post-hazard planning. Without a doubt, the outcomes reported here are crucial for flood risk assessments and hazard management decision-making.

Key words: natural disasters; floods; remote sensing; geographic information system, multi-criteria evaluation; weighted overlay.

Introduction

Flooding is one of the utmost common hazards among terrible natural hazards that poses a serious threat to society due to its devastating effects on people's lives and socioeconomic conditions. In developing countries, floods have devastating consequences, especially for the local poor rural population. [1] investigated that extreme events like flooding are getting more severe as a result of hydrological, topographic and meteorological conditions [2]. Flooding is also fueled by rapid urbanization and climate change[3]. The impacts of flood are unavoidable but can be reduced by implementing suitable management and modification techniques. As a result, assessing possible flood risk zoning is critical for implementing mitigation measures.

The flood risk quantifies flood damages and losses which take into account social, physical, hydrodynamic, physio-climatic, and environmental determinants. The flood risk quantifies both danger and susceptibility, and their summation or multiplication [4]. Owing to data scarcity analytical determination of flood risk is very difficult and time consuming [5]. Instead of full risk analysis, computational modeling and index-based analysis are widely used to measure the flood hazard [6]. Hence, for developing disaster mitigation strategies it is very important to assess the flood hazard.

Hydrodynamic and hydrological models are excessively used for flood simulation at catchment scale. These models are based on extensive data record. The application of hydrodynamic models is challenging task owing to data scarcity. For preliminary studies index based techniques are highly preferred as they are based on limited parameters[7, 8]. It is well-founded knowledge that index based techniques are based on various determinants namely digital elevation models (DEMs), hydrological and geomorphological characteristics, terrestrial determinants, economic, social and infrastructure conditions [9]. Some researchers focused on rehabilitation issues and mitigation policy[7]. However, the endanger spatial extent delineation plays vital role in disaster risk reduction and early warning. Remote sensing and Geographic Information System (GIS) techniques have proven effective in accurately evaluating flood hazards. In the analysis of hazards and vulnerabilities, various methods, such as GIS overlay analysis [9], multi-criteria decision analysis (Lee G, Jun KS, Chung ES 2015), fuzzy method (Malczewski J 2006), and others, have been employed. Integrating Geographic Information System (GIS) with multi-criteria decision analysis (MCDA) offers a range of approaches to enhance decision-making by analyzing and synthesizing geographical data and user expectations. The MCDA method, when combined with GIS, is frequently utilized to assess the vulnerability of areas to flooding due to its adaptability in considering diverse and overlapping factors (Mohamed AE 2013).

Literature shows that the number of parameters is not fixed for index based techniques. Different researchers used different factors while delineating potential flood hazard zones[7, 10]. The principle goal of the current research is to demarcate potential flood hazard zones under two scenarios; firstly, to evaluate the effects of both rainfall and land use land cover changes on potential flood hazard zonation, secondly, to evaluate the influence of land use land cover change on potential flood hazard zonation under constant rainfall. Finally, the results were validated by 2010 flood hazard.

Materials and Methods

Study area

Khyber Pakhtunkhwa, commonly referred as KP or KPK, is one of Pakistan's four provinces. It is situated in the country's northwestern area, along the Afghanistan–Pakistan border (Figure 1). It is situated between the longitudes of 70.00144°E to 74.14363°E and the latitudes of 31.04418°N to 36.92360°N. KP province has an area about 75775 sq. km. The study area has ten major rivers flowing in it. Major rivers having greater impact on the area naming Swat, Kabul, Kunhar, Tochi, Gomal, Kurram, Kohat, Panjkora, Chitral and the prodigious indus. KP climates fluctuates enormously. The air is typically relatively dry; the temperature range is fairly wide on a daily and annual basis. The province climate varies with altitude. Northern areas encounter cold climate where the temperature rises towards south.

https://doi.org/10.24949/njes.v16i1.739

Most of the province's weather remained cold and dry, with the exception of particularly cold and hilly places. Precipitation varies around the province, although it averages roughly 16 inches per year. The province also has some of Pakistan's wettest areas on its eastern border, particularly during the monsoon season, which lasts from mid-June to mid-September
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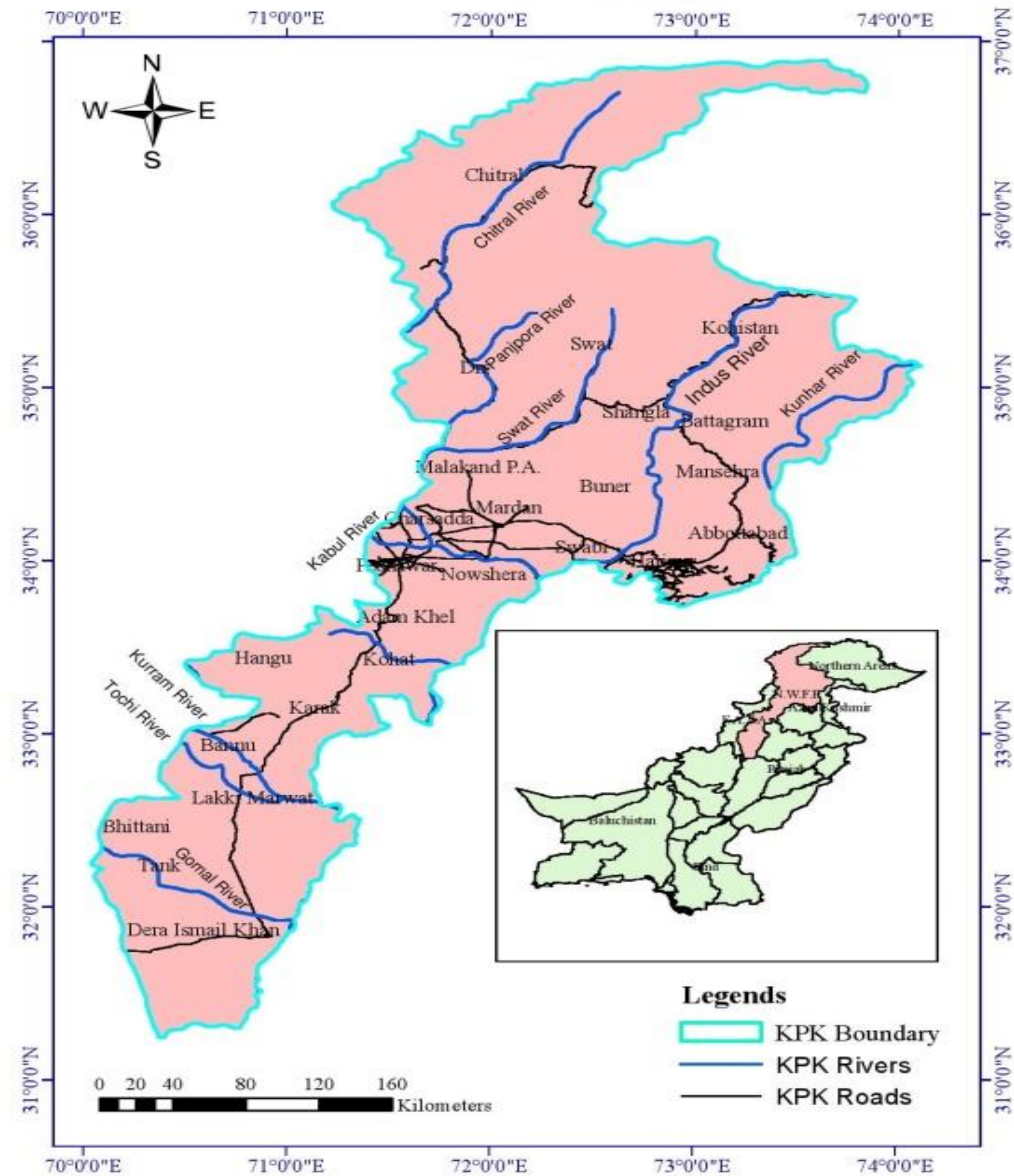

Figure 1: Map of KPK Pakistan

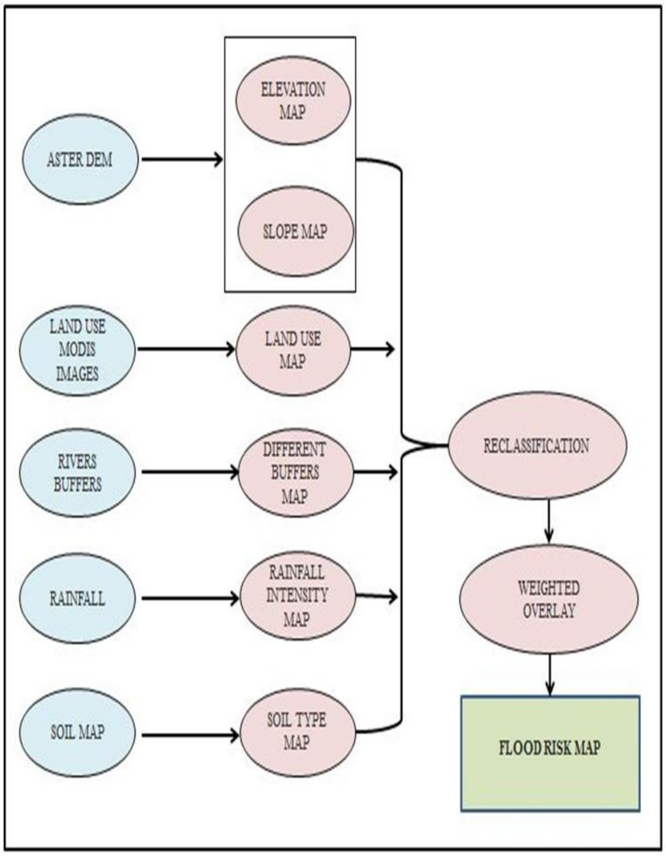

Figure 2: Potential flood risk zoning methodology

Sources of Data

This study's methodology was purely geospatial, with the majority of the data coming from secondary sources. The Geographic information system GIS based multi-criteria evaluation (MCE) method was used to create a flood risk-vulnerability map for KPK by merging several datasets. The following secondary data were used in the study:

I. The study area boundary in shapefile format downloaded from DIVA GIS website (https://www.diva-gis.org/gdata).
II. ASTER Global Digital Elevation Model (GDEM) data of 30-meter resolution was obtained from NASA's Earth Data website (https://earthdata.nasa.gov/)
III. Elevation and slope map: created using the DEM data.
IV. Land Use Land Cover (LULC) was downloaded from United States Geological Survey (USGS) website (https://earthexplorer.usgs.gov/).
V. Using ArcGIS environment parallel buffers at various gaps/distance were drawn from study area major rivers as mentioned in Table 1.
VI. Data regarding rainfall was obtained from the Global Weather website (https://globalweather.tamu.edu/). It is made up of a number of bands that are linked to the year or month that is provided. For the yearly rainfall map or mean rainfall map, the appropriate month's bands were interpolated.
VII. Soil information was obtained from the Food and Agriculture Organization's (FAO) website (http://www.fao.org/). The extracted soil information was classified into three types: rock/gravels/, sandy clay loam, and clay.

Flood Hazard Analysis

Flood hazard exploration was carried out to demarcate the risk zones ranging from very low to very high-risk zones. This study focuses on specific independent parameters, namely Elevation (E), Buffers from rivers (B), rainfall (R), land use (L), slope (S) and soil (S) abbreviated as “EBRLSS”. These parameters together encapsulating the methodology applied in this research. The research methodology is demonstrated by Figure 2.

An analysis of the parameters utilized by various authors reveals commonalities in the geospatial datasets employed. Rainfall intensity and land use changes influence was assessed using two scenarios: firstly, to evaluate the combined effect of rainfall and land use change on potential flood hazard zonation’s, secondly, to determine land use/cover changes influence on potential flood hazard zonation under constant rainfall.

Elevation and Slope

Elevation plays key role in the spread and depth of flooding[11]. The steepness of a slope influences the flow and flooding of a certain region. During floods, low-lying regions with gentle slopes are more likely to be flooded than places with steep slopes. The plane and flat terrains declines water runoff by enhancing infiltration in pervious strata[12]. From the downloaded DEM data elevation map for the study area was extracted. The extracted elevation map was categorized into five classes ranging from 128-821, 821-1837, 1837-3042, 3042-4174 and 4174-7701 meter as obvious from Figure 3(a). Slope was computed using surface analysis tool of spatial analyst in ArcGIS. The slope was classified into five classes namely 0-2, 2-5, 5-8, 8-13 and 13-67 % as obvious from Figure 3(b).

River Buffers

The distance from rivers is critical for assessing flood risk. Flood risk is greatest in floodplains and diminishes as distance from the river increases [13]. Parallel buffers were drawn around the KPK Rivers using proximity analysis in ArcGIS. The parallel buffers were classified into seven classes namely 0-1000, 1000-2000, 2000-5000, 5000-10000, 10000-15000, 15000-20000 and 20000-25000 meter as obvious from Figure 3(c).

There are ten main rivers: The Indus, Swat, Panjkora, Chitral, Kabul, Kunhar, Kurram, Kohat, Tochi, and Gomal, as well as a higher catchment Nalla, the Budni Nalla, which joins the Kabul River after crossing through the KPK tributaries region. The rivers were buffering at different intervals depending upon the discharge. The small tributaries like Panjkora, Kurram, Tochi, Gomal, Chitral, Budni Nalla along Kohat were buffered from 1 Km to 2 Km while the great river Indus was buffered from initial interval of 1 Km to 20 Km, Swat and Kabul rivers from 1 Km to 15 Km and combination of the Indus, Swat and Kabul from 1 Km to 25 Km. Large rivers pose high risk of flooding due to its high runoff volume and high extent spread during the flood.

Geology (Soil Type)

Soil data was extracted for the study area using extract by mask tool of ArcGIS. The soil data of the understudy area has been classified into three groups namely Rock/Gravels, Sandy Clay Loam and Clay as demonstrated by Figure 3(d). Surficial geology plays important role in flooding because it influences permeability of land and their relative surface runoff [14, 15]. Clayey soils tend to have a higher potential for influencing flooding compared to rock/gravels or sandy clay loam. Clay soils have low permeability, meaning they do not allow water to easily pass through them. When clay soils become saturated with water, they have a limited ability to absorb and retain additional water, resulting in increased surface runoff. This can lead to higher levels of runoff during rainfall events and a greater likelihood of flooding. On the other hand, rock/gravels typically have high permeability, allowing water to infiltrate more easily. Sandy clay loam soils can have a moderate level of permeability, depending on the specific composition.

Annual Rainfall Intensity

Floods are mainly caused by extreme precipitation. Flood incidents are influenced by the combination of precipitation factors (rainfall quantity, intensity, interval, and spatial distribution). River discharge increases with increase of rain, causing them to overflow (Samanta et al. 2018). Haripur, Abbottabad, Malakand, Mansehra, and Swat have slightly higher rainfall intensity than the rest of the KPK. The minimum and maximum rainfall is higher in 2010 (1382-1728mm) followed by 2006 (1275-1575mm), 2014 (627-1153mm), 2002 (818-1015mm) and 2018 (765-945mm) as obvious from Figure 4.

Land use land cover (LULC)

Using ArcGIS tool naming “Extract by Mask” Land use data was extracted from downloaded USGS land use land cover data. Various types of land uses (grasslands, water bodies, forest, non-vegetated lands, urban and built-up lands) of different years are demonstrated by Figure 5. LULC changes influence hydrological processes by altering interception rates, soil moisture, evapotranspiration (ET), infiltration, and groundwater recharge, leading to changes in overland flow, streamflow and flood frequency. Literature shows that both land use and climate change are the primary determinants influencing streamflow [16, 17].

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KPK land use prediction was carried out by CA-ANN model using MOLUSCE plugin of QGIS. To begin, land use statistics of 2002 and 2006 downloaded from United States Geological Survey (USGS) website were utilized to forecast land use in 2010. Later, the accuracy and kappa value of the anticipated 2010 land use map were compared to downloaded USGS website land use, which were 81.35 percent and 0.83 percent, respectively. For predicting year 2050 land use authentication between 2002 and 2018 land use was used.

The percentage compositions of land use for different years are demonstrated in Figure 6. Figure 6 illustrates an increase in the percentage composition of urban and built-up areas from 1.25 to 1.48. Because of the increased impervious surface area, urbanization increases surface runoff (Afed Ullah et al. 2018, Khan et al. 2017a, Khan et al. 2017b).

Land Use/Cover future Prediction

Cellular automata based on artificial neural network (CA-ANN) along QGIS plugin module of Land Use Change Simulations (MOLUSCE) was used for predicting year 2050 land use. As land use drivers, slope and aspect factors were utilized. Land use in 2002 and 2006 were used to estimate land use in 2010 in order to test the model's effectiveness, and then land use in 2050 was anticipated.

Multi-Criteria Decision Analysis (MCDA) and Weighted Overlay Analysis

MCDA technique permits map layers to be weighted to highlight Elevation, Buffers from rivers, rainfall, land use, slope and soil parameters their relative influence. Weights based on literature review, field knowledge, and studies in similar geographical regions, the relative weight of each layer is used in weighted overlay analysis to produce potential flood hazard maps. Weighted overlay analysis is widely used in multi-criteria problems. Potential flood risk mapping need the determination of contributing determinants which are subjected to data availability. In the current study, we hypothesized that EBRLSS parameters are the dominant factors causing flooding in the study area. Thematic layers were produced for each EBRLSS parameter multiplied by its assigned weight for generating the final potential flood hazard map

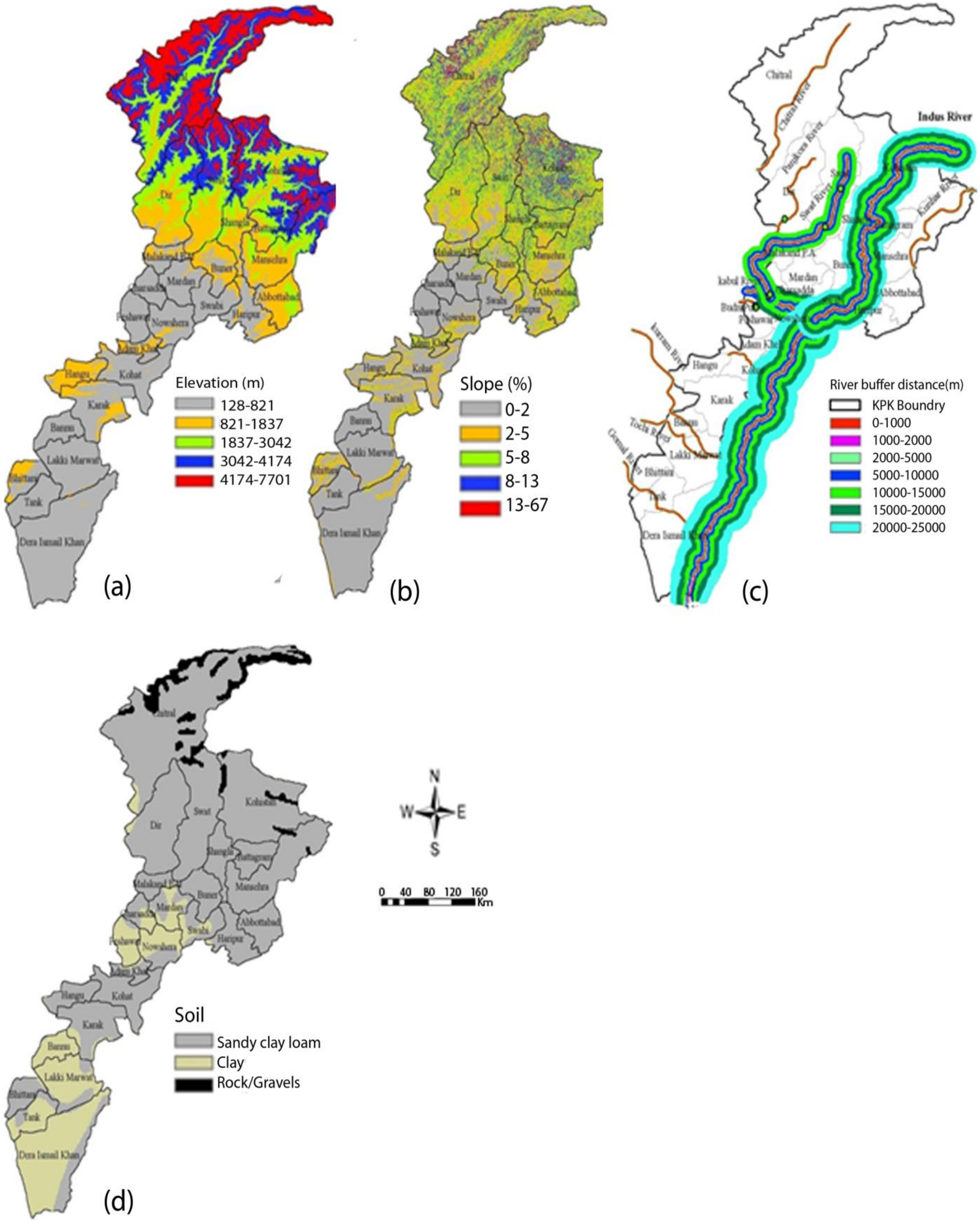


Figure 3: Map demonstrating KPK (a) elevation (b) slope (c) rivers buffers (d) soil

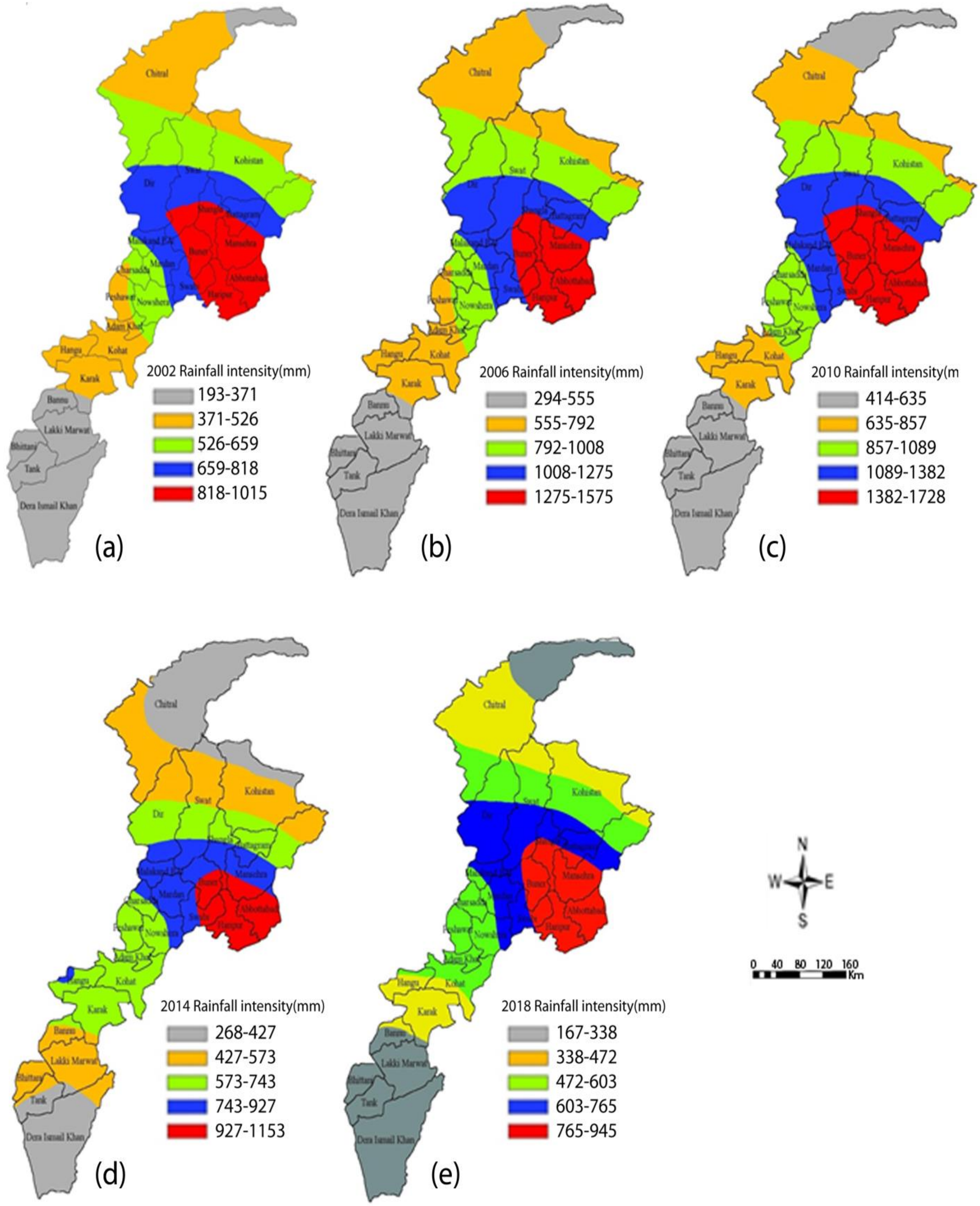


Figure 4: KPK annual rainfall (mm) (a) 2002, (b) 2006, (c) 2010, (d) 2014, and (e) 2018

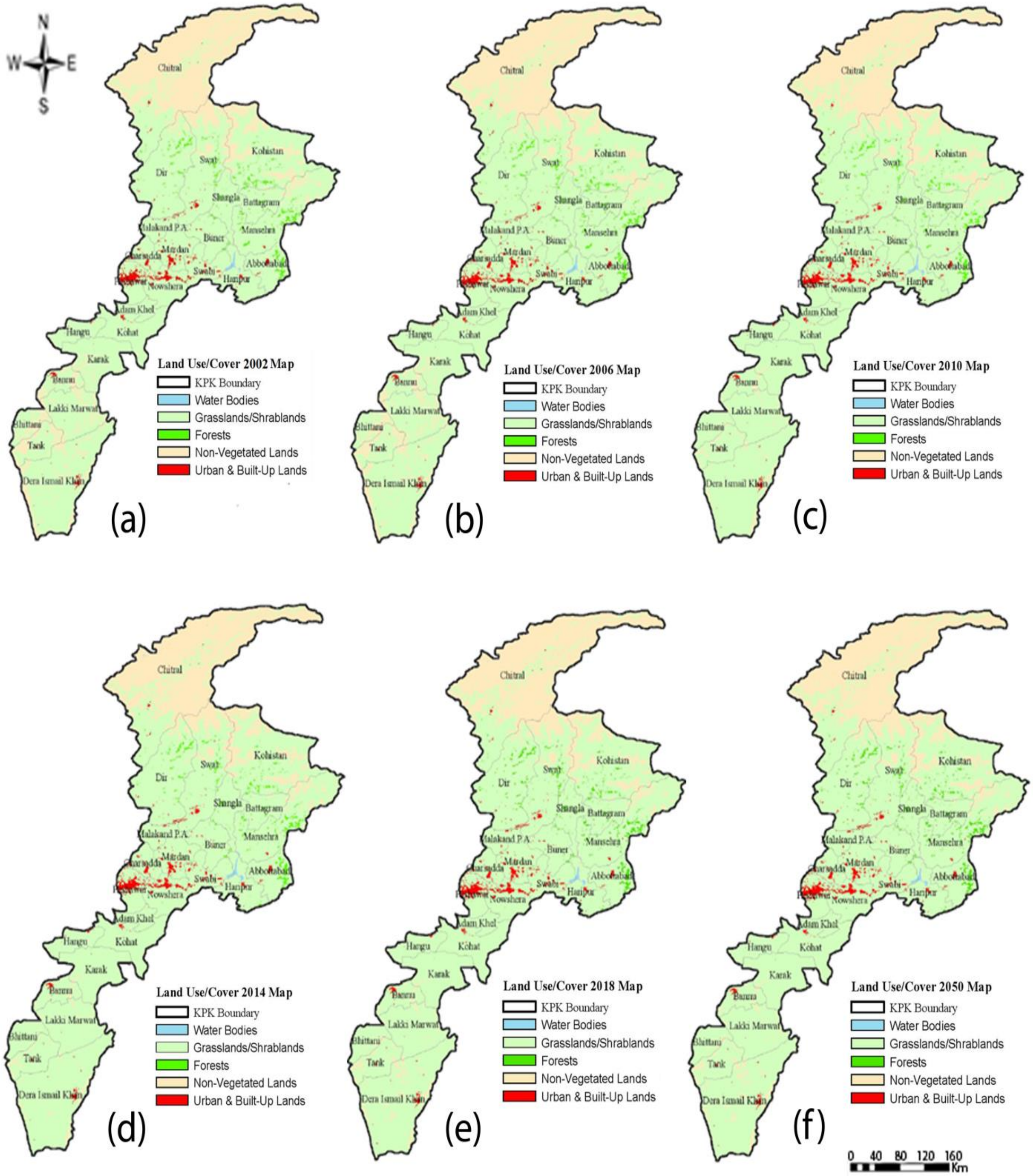
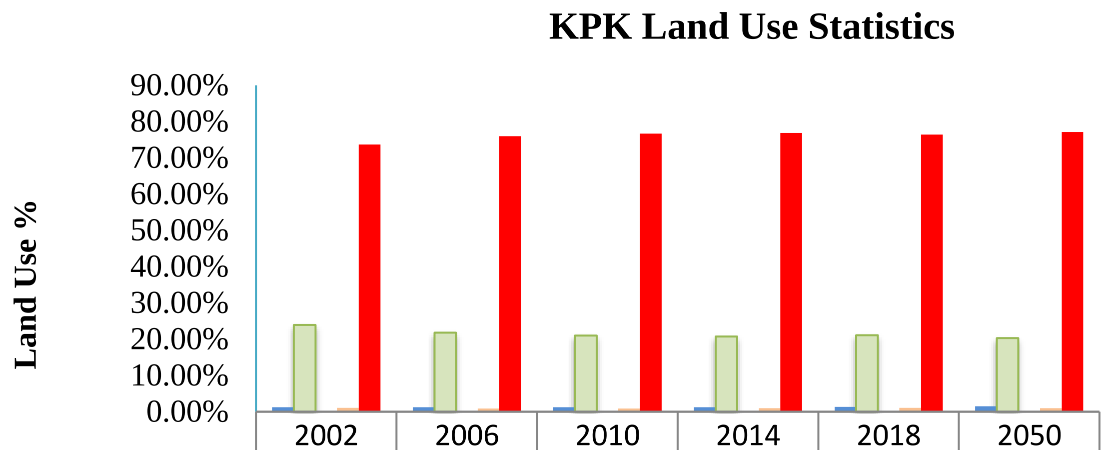


Figure 5: Land use maps of KPK for (a) 2002, (b) 2006, (c) 2010, (d) 2014, (e) 2018, (f) 2050



	2002	2006	2010	2014	2018	2050
Urban and Built-up Lands	1.25%	1.26%	1.27%	1.28%	1.30%	1.48%
Non Vegeted/Barren Land	23.90%	21.76%	21.03%	20.72%	21.06%	20.27%
Water Bodies	0.12%	0.14%	0.14%	0.16%	0.13%	0.15%
Forests	1.06%	0.90%	0.90%	1.00%	1.10%	0.99%
Grasslands/Shrublands	73.67%	75.94%	76.67%	76.83%	76.40%	77.12%

Figure 6: Land use % composition of KPK.

Spatial Data Preprocessing

Spatial data is necessary for the weighted overlay process's criterion. The criteria are based on the EBRLSS variables. Elevation, slope, and watershed were derived from DEM. The KP Rivers were digitized using satellite imagery, and parallel buffers spanning various distances were generated using ArcGIS. Surface interpolation was used to build a raster precipitation map from the downloaded data. A land use map for the research region was created using ArcGIS on USGS website land use data, and a polygon map for soil types was created using downloaded soil data. The above mentioned factors were converted to the same resolution i.e. 30 mx30 m.

Factors influencing flood potential

It is well-founded knowledge that many factors effects flood at global scale [18]. Some parameters are extensively used in flood mapping based on their importance. Some studies show that accurate results can be obtained by using specific least number of variables[19]. The existing research is based on the most influential parameters namely slope, rainfall intensity, distance from rivers, soil, LULC and altitude.

Criteria weights and rating of the classified thematic layers

This procedure is divided into three conceptual phases. To begin, each raster layer is given a percentage weight to indicate its relevance in the analysis. Second, the values within each raster layer are prioritized (suitability scale) to enable comparison of the various forms of information included inside each raster layer. Finally, all raster layers in the study are superimposed. The individual raster cell values ranking is multiplied by weighted layer then added to the ratings of former raster cells that it overlays. Each criterion under consideration was reviewed in order of preference throughout the ranking phase. Straight Rating (that is, most important = V, least important = I) is one of the most common methods of ranking. The ranking used in this research correlates to the degree of flooding, which is as follows: very high = V, high = IV, moderate = III, low = II and very low = I (Samanta et al. 2018) as illustrated in Table 1.

The resulting raster is a flood danger map that displays which regions are affected by the various levels of flooding indicated above. Increase the overall weight sum to 100 to execute the weighted overlay analysis. With the use of a common measuring scale, the weighted overlay combines several raster layers and assigns each raster a weight based on its importance.

Results and Discussion

Potential flood hazard mapping

The weights and their relevant rates of input parameters were merged using the weighted overlay analysis approach in ArcGIS environment for generating research area flood risk-vulnerability. The developed flood risk-vulnerability maps were categorized into five different zones ranging from the very low risk to the very high-risk zones. Flood incidence chances will be very less or zero where the area is marked in very low risk zone. The flood chances are low in moderate risk zones during ordinary situation but it may be risky in case of intense rainfall or when water exceeds the dam storage. In very high and high-risk zones floods can occur even in seasonal as well as infrequent rainfall with least damages, but the damages will be alarming in case of intense rainfall [16, 17].

Figure 8 & Figure 9 demonstrate that 22% area of the province lies in high and very high risk zones. The high and very high-risk zones are minor in comparison gross area of the province. However, flood incidents occur frequently in low lands, area with an undulating terrain and feasible water bodies, societies frequently establish themselves in low-lying areas, particularly those near rivers. Figure 7 demonstrates that urban and built-up area located on river banks are highly vulnerable to floods (high and very high risk zones) as per the results. Communities situated in high-risk zone comprises of; Peshawar, Charsadda, Nowshehra, Swat, Malakand, Swabi and Mansehra. Flooding derails industrial development and ruins millions of dollars' worth of land. Figure 6 depicts the locations where the majority of the bridges across the rivers failed and buildings in close proximity to the river were completely inundated during the 2010 severe flood event. Charsadda and Nowshehra were totally submerged during the wet season. Relocation remains implausible, given that the precipitation spell lasts just four months out of twelve. This indicates that there are several approaches to dealing with the frequent floods.

Table 1: MCDA Parameters of KPK

Parameters	Class	Rank	Rating Index/ Risk vulnerability	Weight (%)
Distance/buffers as of rivers (meter)	≤500 -- 2000	V	Very High Risk	25
	2500 -- 5000	IV	High Risk	
	5000 -- 10000	III	Moderate Risk	
	10000 -- 15000	II	Low Risk	
	15000 -- 25000	I	Very Low Risk	
Rainfall intensity(mm) 2002	193 – 371	I	Very Low Risk	16
	371 - 526	II	Low Risk	
	526 - 659	III	Moderate Risk	
	659 - 818	IV	High Risk	
	818 - 1015	V	Very High Risk	
Elevation/Altitude (meter)	128 -- 821	V	Very High Risk	22
	821 -- 1837	IV	High Risk	
	1837 -- 3042	III	Moderate Risk	
	3042 -- 4174	II	Low Risk	
	4174 -- 7701	I	Very Low Risk	
Land use/Land Cover	Forests	II	Low Risk	10
	Cropland	III	Moderate Risk	
	Urban and Built-up Lands	V	Very High Risk	
	Barren/Sand/Rocks	IV	High Risk	
	Water Bodies	I	Very Low Risk	
Slope (%)	0 -- 2	V	Very High Risk	22
	2 -- 5	IV	High Risk	
	5 -- 8	III	Moderate Risk	
	8 -- 13	II	Low Risk	
	13 -- 67	I	Very Low Risk	
Soil/Geology categories	Rock/Gravels	III	Very Low Risk	5
	Clay	II	Moderate Risk	
	Sandy Clay Loam	I	Low Risk	

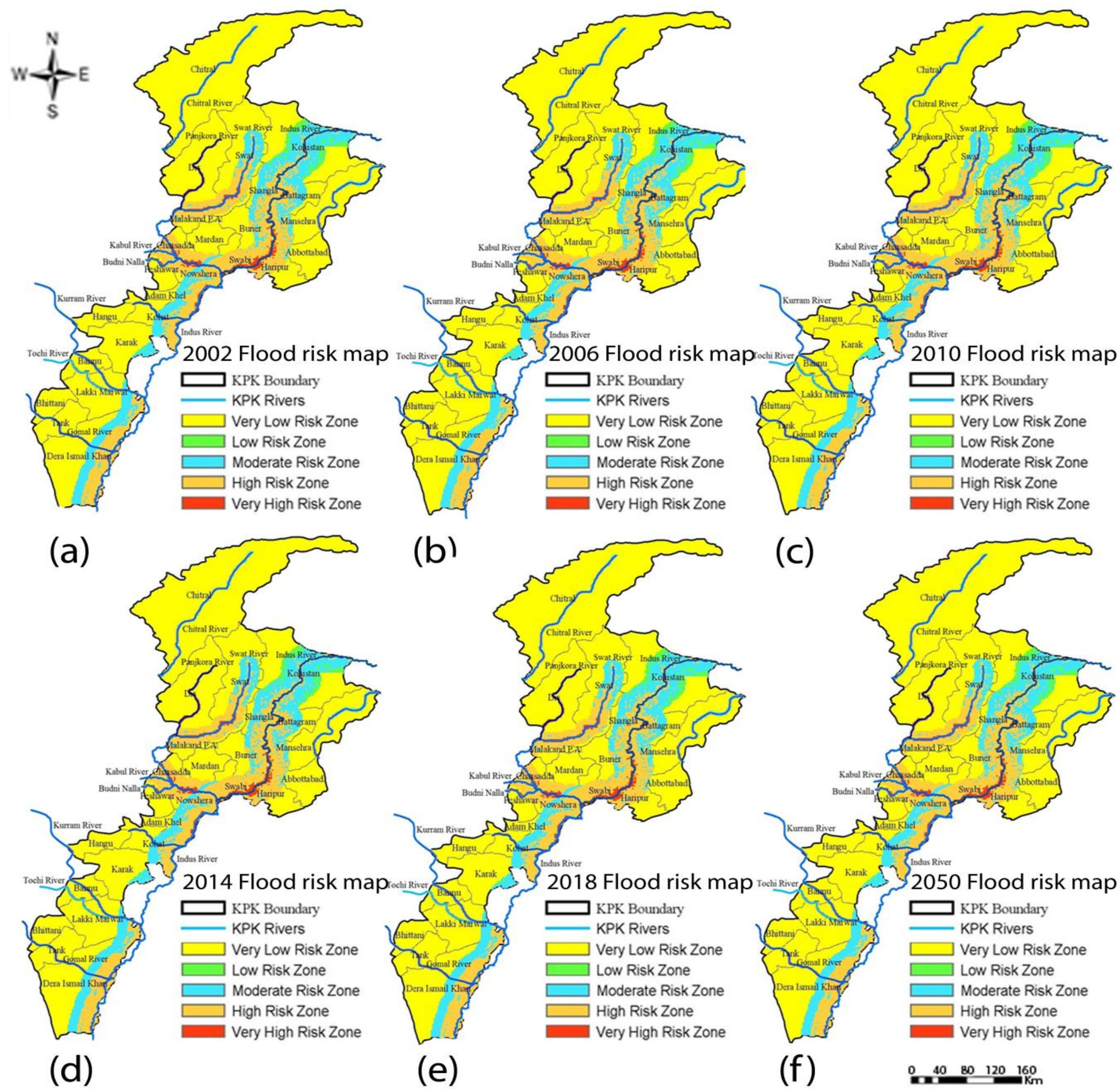
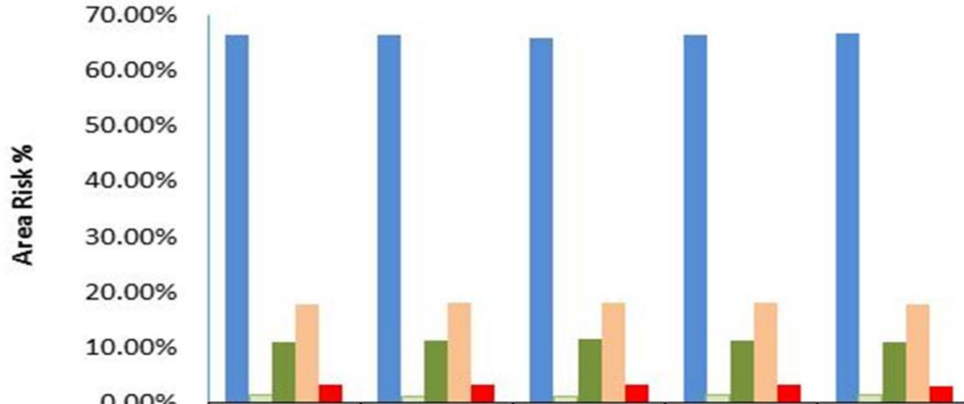


Figure 7: KPK flood risk vulnerability maps (a) 2002, (b) 2006, (c) 2010, (d) 2014, (e) 2018 and (f) 2050.

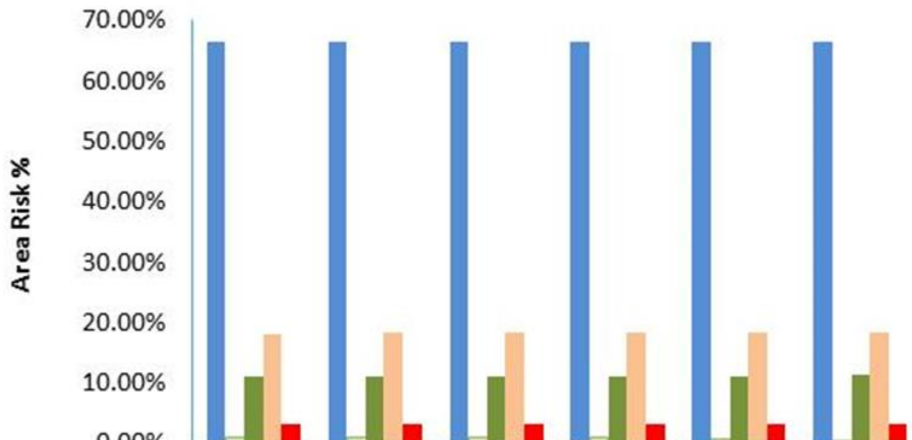
Land use and rainfall Impacts on potential flood mapping

The current research is based on two possibilities. First, consider the combined impact of land use and rainfall on possible flood maps. Second, changes in land use have an impact on possible flood mapping. Figure 8 shows that for scenario one, a rising trend in percentage area of flood zones parallel to rainfall record was observed. The percentage area of extremely high, high, and moderate danger zones is greater in 2010, followed by 2006, 2014, 2002, and 2018, while the share of extremely low and low risk zones is lower in 2010, it is higher in 2006, 2014, 2002, and 2018. About 22% of the overall area is comprised of the extremely high and high danger zones. The results indicated that flood risk zonation followed a similar pattern to rainfall records, indicating that rainfall is the most influential element determining potential flood zonation. According to Scenario 2, as shown in Figure 9, the percentage of the flood risk zone increased from 2002 to 2050. From 2002 to 2050, the percentage of urban and built-up land increased from 1.25 to 1.48 percent. The growing tendency of urban and constructed areas may be attributable to the increase in percentage flood risk zonation region. Because of the increased impervious surface area, urbanization increases surface runoff, which increases streamflow and may induce flooding (Afed Ullah et al. 2018, Khan et al. 2017a, Khan et al. 2017b.)



	2002	2006	2010	2014	2018
Very Low Risk Zone	66.54%	66.33%	65.91%	66.36%	66.62%
Low Risk Zone	1.33%	1.15%	1.03%	1.30%	1.36%
Moderate Risk Zone	11.13%	11.25%	11.50%	11.15%	11.10%
High Risk Zone	17.80%	18.02%	18.14%	17.97%	17.76%
Very High Risk Zone	3.20%	3.25%	3.42%	3.22%	3.16%

Figure 8: Flood risk-vulnerability statistics for combined influence of rainfall and land use



	2002	2006	2010	2014	2018	2050
Very Low Risk Zone	66.42%	66.42%	66.42%	66.42%	66.42%	66.42%
Low Risk Zone	1.04%	1.00%	0.96%	0.92%	0.84%	0.51%
Moderate Risk Zone	11.13%	11.14%	11.15%	11.16%	11.19%	11.26%
High Risk Zone	18.23%	18.25%	18.27%	18.28%	18.31%	18.44%
Very High Risk Zone	3.18%	3.19%	3.20%	3.22%	3.24%	3.37%

Figure 9: Flood risk-vulnerability statistics land use change influence only.

Model validation

The current study's flood risk-vulnerability maps were confirmed using a satellite-based historical 2010 flood inundation map, as shown in Figure 10. Adjacent areas to rivers were mainly affected by 2010 flood. This research's flood hazard maps were compared to a 2010 flood inundated map, where the very high risk zone and high risk zone lie inside the inundated area, demonstrating the validity of the current analysis. Figure 11 demonstrates research's flood map very high risk zone points (P1-P8) and mentioned points are compared with flood 2010 pictures. The country's five major rivers flow from north to south, including the great Indus and its tributaries, the Ravi, Sutlej, Jhelum, and Chenab. Initially Swat valley was impacted due to burst in River Swat. Flood in KPK and other provinces damaged human settlements, infrastructure and crops. The combined consequences of 2010 flood badly impacted the country economy

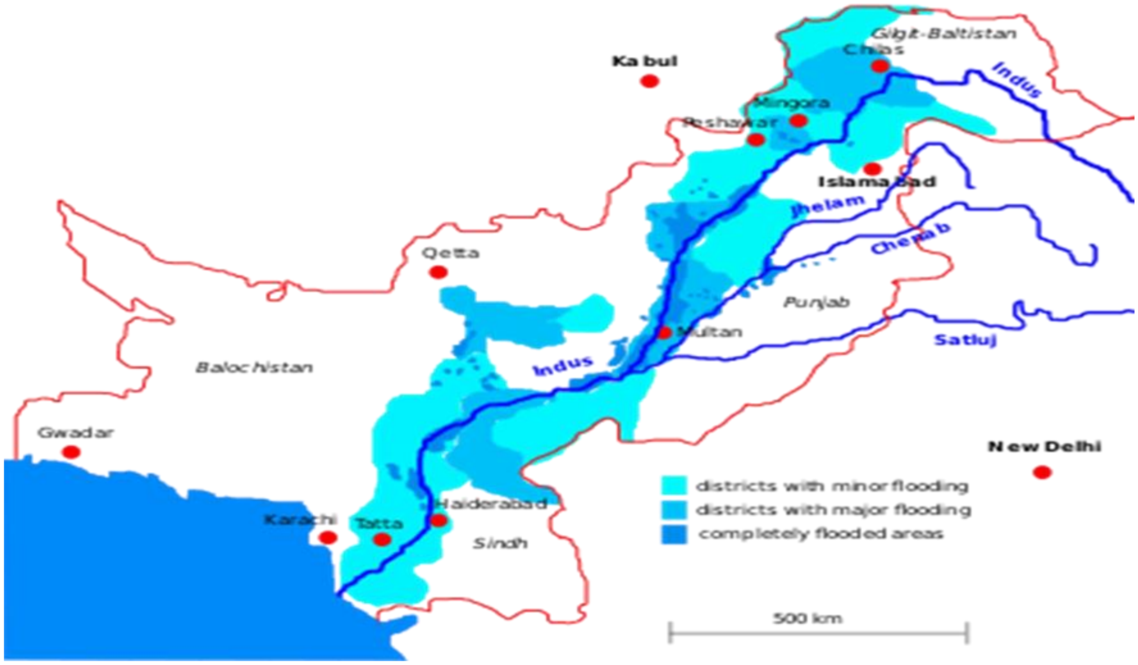


Figure 10: Flood August 2010 flooded areas

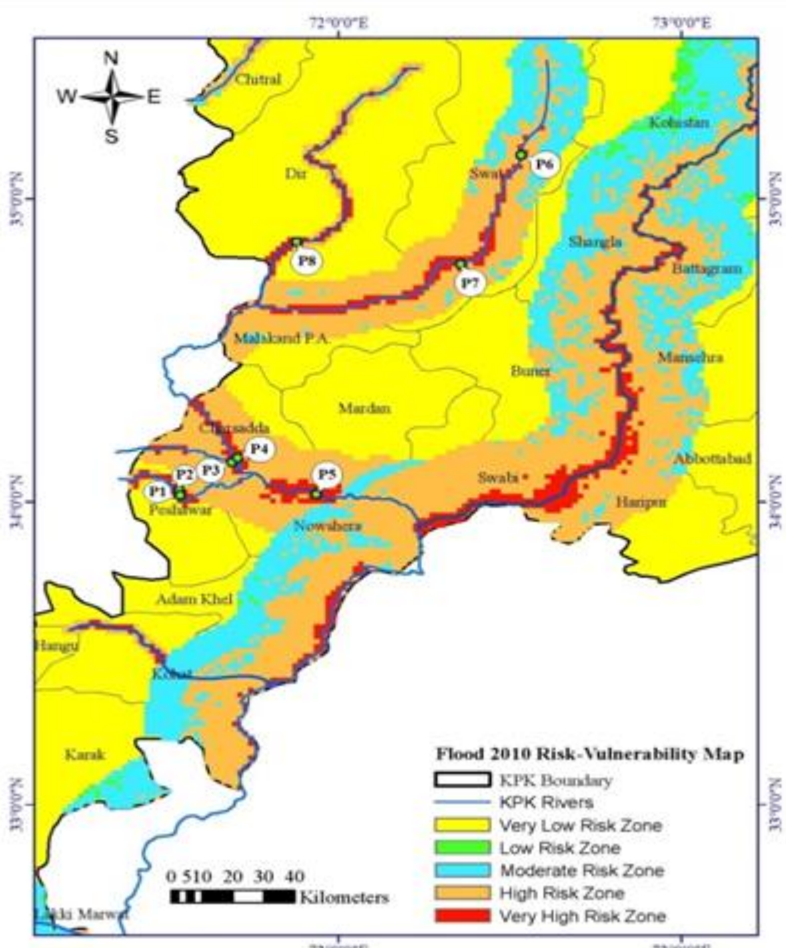


Figure 11: P1-P8 (Very High Risk Zone) Points during 2010 Flood

Figure 12: P1 Warsak road flood 2010 very high risk Zone

Figure 13: P2 Warsak road flood 2010 very high risk zone (71.535, 34.037)

Figure 14: P3 flood 2010 Saraydaryab Bridge Kabul River (71.689, 34.129)

Figure 15: P4 Flood 2010 Khylaee Bridge Swat River (71.706, 34.144)

Figure 16: P5 Flood 2010
Nowshera city
(71.934, 34.022)

Figure 17: P6 Flood 2010
Madyan Swat
(72.538, 35.145)

Figure 18: P7 flood 2010
Mingora Swat
(71.689, 34.129)

Figure 19: P8 flood 2010
Timergara Bridge
(71.876, 34.867)

Conclusion

The purpose of this study was to identify potential flood danger risk zones in KPK. Each thematic layer was given a weight, which was then overlaid using ArcGIS and validated using Pakistan's historical 2010 flooded map.

Computed weights of each layer based on literature review, field knowledge, and studies in similar geographical regions, were used in weighted overlay analysis to produce potential flood hazard maps. The final hazard map was created by linearly integrating the criteria and their weights. The results indicated 3.37% (2553.62 Km^2) falls in extremely high risk, 18.44% (13972.91 Km^2) falls in high risk, 11.26% (8532.27 Km^2) falls in moderate risk, 0.51% (386.45 Km^2) falls in low risk, and just 66.42% (50329.76 Km^2) falls in very low risk areas respectively. When compared to the entire area covered, the cumulative area for the high and extremely high-risk zones is low. Flooding is exacerbated by rainfall and development.

Furthermore, the projected flood maps and the 2010 inundation map are quite comparable, showing the validity of the study.

Remote sensing, in conjunction with ArcGIS, is critical in identifying possible flood danger zones. The present approach's applicability and reliability are dependent on secondary data availability and resolution. Incorporating greater resolution and intense field data can improve accuracy. Furthermore, the lack of high temporal scale remote sensing data limits flood hazards mapping.

According to the current study, the flood hazard index technique is extremely successful in detecting probable flood danger zones, which may support flood management decision-makers. Accommodation must be limited inside estimated flood risk zones; also those who are already residing in these areas should be relocated. The current method can be utilized anywhere on the globe, particularly in countries where data is rare.

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