Assessment of multi-components and sectoral vulnerability to urban floods in Peshawar – Pakistan

Published in:
Natural Hazards Research

Publication Status:
Published (in print/issue): 14/12/2023

DOI:
10.1016/j.nhres.2023.12.012

Document Version
Author Accepted version

Assessment of Multi-components and Sectoral Vulnerability to Urban Floods in Peshawar – Pakistan

Abstract

Over the last two decades, urban floods and their impacts have been on the rise worldwide, owing to both climatic changes and human activities. The present study examines different at-risk elements, such as residential, commercial, and critical facilities, to evaluate their multi-components of vulnerability to urban floods in Peshawar, Pakistan. Based on the impacts of urban floods, the weightage of each component of the vulnerability for the selected elements at risk is defined. The study presents and uses the modified Fisher's ideal quantity index to combine the different vulnerability components into a single value. Additionally, the Patnaik and Narayan vulnerability index is employed to generalize sector-wise vulnerabilities across the study area. The results show that the old physical infrastructure of commercial and manufacturing units in the Kohati Gate area is highly vulnerable to urban floods, while the residential units are the least susceptible due to their distanced location from the drainage system. In Hayatabad, encroachments along the torrent's sides, affecting housing and educational institutions, contributed to increased vulnerability to urban floods, despite their relatively lower physical vulnerability. The study provides a new platform for understanding the multi-components of vulnerability to urban floods and tackling the challenges posed by urban floods effectively.

Keywords: Multi-components vulnerability assessment; Urban floods; Modified Fisher's ideal quantity index (mFIQI); Peshawar; Pakistan

1. Introduction

Urbanization is very rapid in developing countries without proper planning (Zhang, 2016). The damages of urban floods are on the rise, particularly in the cities slums, squatter settlements, and rural-urban fringe areas (Berndtsson et al., 2019; Chen et al., 2015; Hammond et al., 2015). These areas are not only thickly populated but also lack disaster preparedness and emergency services, which makes the situation further aggravated (Osti and Nakasu, 2016; Serre and Heinzlef, 2018). The risk of urban floods is considered to increased significantly in the near future due to continuous changes in the earth's demography and climate change (de Almeida et al., 2018; Echendu, 2023; Güneralp et al., 2015; O'Donnell and Thorne, 2020). The city of Peshawar is exposed to both fluvial & pluvial floods. However, in terms of urban flooding, nature is pluvial because such events mostly occur due to torrential heavy rainfall for a long period of time (Salman et al., 2021). Urbanization, improper retention and sewerage system, solid waste management, decreasing soil absorption capacity, lack of urban flood early warning system (EWS), and encroachment around the main drainage system further exacerbate its effects (Hamidi et al., 2020; Tayyab et al., 2021). In the monsoon and western depression season, the local drainage system saturates and causes damage to property as well as the local economy in the urban areas of Peshawar (Abbas et al., 2023; Khan et al., 2020; Rebi et al., 2023; Ullah et al., 2018). The floods of 2008, 2010, 2012, 2014, 2015, and 2016 are the recent most floods in Peshawar, which caused widespread physical & economic losses (Government of Khyber Pakhtunkhwa, 2016, 2017; Waseem and Rana, 2023). The paradigm shift in the disaster risk reduction (DRR) strategy is the need of the day at the government level against urban floods because the emphasis is given more on post-disaster management rather than the pre-disaster management phase of urban floods (Khan et al., 2022; Rahman and Shaw, 2015; Shah et al., 2020).

It is a well-known fact that effective and efficient DRR relies on scientifically sound disaster risk assessment (Aerts et al., 2018; Gall et al., 2015; Hussain et al., 2023). The disaster risk assessment of urban floods is itself a compound and complex process of interrelating hazard, exposure, vulnerability, and capacity. Assessment of vulnerability to urban floods is one of the integral parts of this process which nature is itself compound and complex (Jamali et al., 2018; Rana and Routray, 2018a). It is a compound process of its components (physical, economic, social and attitudinal) assessment, which is also changed with the elements at risk (Biswas, 2023). The complexity involved in its interrelationship with the magnitude of hazard, dynamic exposure, and capacity (Abebe et al., 2018; Erena and Worku, 2019; Ikram et al., 2023; Rana et al., 2021; Rana and Routray, 2018b). However, in the present study, the magnitude of hazard and exposure is considered a binary constant based on the historical records of urban floods in the study area. Based on the impacts of urban floods and field data, weightage for the components of vulnerability is calculated which is different for different types of elements at risk. The computation of combining multi-component of vulnerability into a singular expression is carried out on the modified formula of Fisher's ideal quantity index (mFIQI). On one hand, this modified formula calculates the combined effects of vulnerability into sole signature of numerical value while on other hand, it has the capacity to incorporate temporal changes in the vulnerability of the elements at risk. In two different characteristic regions of residential and commercial, the sector-wise vulnerability to urban floods is generalized and ranked on the vulnerability index formula of Patnaik and Narayan (Patnaik and Narayanan, 2009).

Peshawar has always been vulnerable to floods because of its demographic and socio-economic features along with its geographical position in relation to water sources. Most of the oceanic indices shows a positive coherence with extreme precipitation indices particularly Indian Summer Monsoon Index (ISMI) in Pakistan (Hussain et al., 2023). The recent trends show a significant increase in River Kabul annual runoff, particularly from the western depression system (Hussain et al., 2022). In the upper catchment of River Kabul, the accelerated summer warming and stable winter warming increase the surface runoff resulting in a flooding situation (Abbas et al., 2022; Nawaz et al., 2023). A good example is the 2010 floods, which is considered the biggest flood in the history of Pakistan (Rahman and Khan, 2013; Rahman et al., 2023; Ullah et al., 2021). The cause of this flood was the heavy rainfall that lasted for 3 days. This rainwater caused immense pressure on the already poor and inefficient drainage system of the city resulting in heavy physical and economic losses, with 250 families affected and many others dead. The irrigation system was worse affected, resulting in severe damage to the livestock, crop production, damages to farmlands, and loss of foreign exchange due to the destruction of roads, warehouses, shops, orchards, standing crops, and fruit and vegetable reserves (Government of Khyber Pakhtunkhwa, 2016; Government of Pakistan, 2010; Khan et al., 2010; United Nations Development Programme, 2010).

Conventionally, most methods of assessment of vulnerability to floods involve record-based statistical investigation and Geographic Information System (GIS) based drainage system analysis in a particular area (Ouma and Tateishi, 2014; Scionti et al., 2018). In the statistical-based investigation, the data required for all components of vulnerability is either sketchy or missing from the record, particularly for the economic damages in developing countries. The GIS-based analysis and their methods have the capacity to analyze the exposure to floods with remarkable precision (Hussain et al., 2021; Müller et al., 2011; Rahman et al., 2023; Sowmya et al., 2015). Most of the studies focused on social and physical vulnerability assessment (Armaş & Gavriş, 2013; Holand et al., 2011; Kappes et al., 2012; Singh et al., 2019). Economic vulnerability is discussed at the regional level in monetary terms while multi-components of vulnerability are always open-ended (Fuchs et al., 2012; Moret, 2014). However, in the case of vulnerability assessment, it is only confined to a limited number of elements at risk with no component analysis of the vulnerability and/or interrelation with other components of the risk. Similarly, the nature and variation, in the type of vulnerability, of urban flooding are the least considered in the literature. The study focused on the objectives: understanding the nexus of urban development and floods; floods history and vulnerability weightage index; and multi-components assessment with sector-wise ranking. The present methodology of the assessment of multi-components and sector-wise vulnerability to urban floods is a unique attempt to provide a framework that can be used in statistical and GIS platforms. This methodology is the generalized form of multi-components and sector-wise vulnerability assessment to urban floods, which has the capacity to incorporate the methodological development in the vulnerability assessment as well as interlinking its values with the dynamic exposure and specific magnitude of a hazard. The basic essence of this method remains the same on different platforms. Most importantly, it will provide basic results irrespective of the platform or data level. The methodology can adopt the advanced techniques of the assessment of the components of vulnerability or can be attached with any geo-spatial programme as an attribute assessment technique.

2. Data and Methods

The assessment of multi-components and sector-wise vulnerability to urban floods in Peshawar – Pakistan is carried out in six major steps, i.e., identification of affected areas; type & exposure of urban floods; inventory of the elements at risk; indexing of each element at risk; assessment of different dimensions of vulnerability; and generalization of sector-wise vulnerability. Based on the literature review and the reports of the National as well as Provincial Disaster Management Authority, Khyber Pakhtunkhwa (NDMA and PDMA, KP), the urban flooding areas in Peshawar are identified ((Government of Khyber Pakhtunkhwa, 2016; Government of Pakistan, 2010; Khan et al., 2010; United Nations Development Programme, 2010). The most affected areas in the commercial sector are the GT surrounding areas, Peepal

Mandi, Kohati Gate, and University Road. The Union Councils (UCs) 60 and 61 of Tehkaal Payaan and UCs 43 and 44 of Hayatabad are residential areas, which are severely affected by urban flooding (Figure 5). The areas that are vulnerable to urban floods in Peshawar include the Hayatabad area, the Tehkaal Payaan area of the University Road, the commercial areas surrounding Grand Trunk (GT) Road, the economic area of Peepal Mandi, and Kohati Gate (interior). All of these areas have very poor drainage systems making them prone to urban flash floods. Also, the encroachment of flood plains in the western part of the city further enhances their vulnerability to urban flash floods. Similarly, the city area of Peshawar (Andar Shehr) and Peepal Mandi consists of British-era buildings. These buildings have exceeded their expiration period and can collapse at any time. Furthermore, the accessibility routes are very small and congested; at rush hour it becomes very difficult to cover even short distances. This combined with heavy rainfalls in the monsoon season and poor drainage system increases the vulnerability of this area to urban floods (Government of Khyber Pakhtunkhwa, 2016; Government of Pakistan, 2010).

The mixed-method research approach is used for the data collection and analysis (Berman, 2017; Kumar et al., 2019). (Kumar et al., 2020)The primary data is collected from the local residents, Key Informant Interviews (KIIs), and business community through field observations, questionnaires, and semi-structured interviews. The confidentiality ethics statement on questionnaires and KII was based on principal that all information will be coded and only used for research purpose (Wiles et al., 2008). A rapid appraisal survey was conducted to determine the population, sample size, level of confidence, and to reduce the margin of error. The Kohati Gate has small area with almost 100 units of commercial and residential with equal proportion while the selected area in Hayatabad has more than 500 residential units and two small markets. Based on 90% level of confidence, 10% margin of error and considering one third as relative proportion to urban floods; the sample size are 25 and 50 households and all commercial units from Kohati Gate and Hayatabad areas, respectively (Taherdoost, 2017). Looking to the urban flood condition in each site, the judgmental sampling technique is applied to select the most relevant sample from these sites (Taherdoost, 2016). A reconnaissance survey of the physical structures in the selected site is made to identify the residential, commercial, public (schools, hospitals, police station, community centers etc.), critical infrastructure (bridge, roads, retaining walls, telecommunication, canals etc.), and civic utilities (power and water supply structures). The representative buildings are selected from each building type as samples which allows for the transfer of knowledge from in-depth investigations of individual buildings to other buildings with similar characteristics. The qualitative data were collected through KIIs from academia in the University of Engineering and Technology, University of Peshawar; officers in the PDMA, PMD, Peshawar Development Authority (PDA), and Irrigation Department (Kumar, Kumar, & PRABHU, 2020). The results of qualitative analysis are converted to normalized values which also provides a base for the questionnaire of quantitative data collection. The IBM Statistical Product and Service Solutions (SPSS) was used for questionnaires and field observation data to record the variables of the components of vulnerability(Crop, 2015). The nature, elements at risk and vulnerability conditions are different at both sites Therefore in first phase, the relevancy of the variable (question and/or observation) was decided by bivariate analysis through cross-tabulation in SPSS with a Chi-Square test to ascertain the significant association with a *P-value* of 0.05. The qualitative and quantitative data were in different format (nominal, ordinal, interval, and ratio). The vulnerability analysis required data into similar format. Therefor,the data collected from all sources are normalized using Equation. 1.

$$X_{New} = \frac{x - \mu}{\sigma} \quad \text{(Eq. 1)}$$

$$X_{New} = \frac{x - x_{Min.}}{x_{Max.} - x_{Min.}} \quad \text{(Eq. 1a)}$$

and $X_{New} = \frac{x_{Max.} - x}{x_{Max.} - x_{Min.}}$ (Eq. 1b)

Where μ is the mean value, σ is the standard deviation, and x is the variable. Eq. 1a represents a direct relationship, while Eq. 1b represents an inverse relationship.

The probabilistic flood frequency analysis is used for the estimation of flood hazards in the study area (Bhat et al., 2019; Rahman et al., 2013; Sarhadi et al., 2012). The discharge data of rivers and streams at the different gauge stations are available with the Irrigation Department of Khyber Pakhtunkhwa (Government of Khyber Pakhtunkhwa, 2021). The probability of occurrence of an event in any observation is the inverse of its return period. In the present study, the equation and return period are derived from the logarithmic graph (Equation 2). The daily rainfall data are used for the identification of the threshold level of an urban flood in the Peshawar region (Government of Pakistan, 2021). The hydro-morphometric analysis, urban growth, and permeability are studied through GIS analysis. The inter-census relationship among population growth, built-up area, and permeability is analyzed by Pearson Correlation Coefficient (Equation 3) (Government of Pakistan, 1999, 2017 and 2018). The Hydrology tool set from the Spatial Analyst toolbox in ArcMap is used to analyze the Drainage System in Peshawar (Desktop, 2011). The watershed is an up-slope area that contributes water flow as concentrated drainage. The area is delineated from a mosaiced TIFF file of ASTER-GDEM 2 with spatial resolution of 12.5 metre. It is pertinent to mention that all watersheds are analyzed before entering into River Kabul. All contributing watershed areas, stream orders (Strahler), density, altitude, and slope were calculated and mapped through ArcGIS. Google Earth Engine (GEE) is used as a platform for land use identification and classification (Amani et al., 2020). In the present study, GEE used geospatial data from the Landsat satellite program. GEE provides different filters for the selection of required images, e.g., type date, area, cloud, etc. A total of four images have been used in this study. The first two images for 1998 are used to cover the whole area, then two images for 2017. Specific dates for the two images are 08-06-

1998 and 12-06-2017, respectively. Random Forest Classifier technique is used in land use classification. The rest of the tasks of area calculation, exporting maps, and results into shape files are automated in GEE, which are further analyzed in ArcGIS. The summary of the GEE code provides basic information about method, classifier, source of images, date, time, and path etc.

```
var image1 = ee.Image('LANDSAT/LC08/C01/T1_TOA/LC08_151036_20170612'); var image3 = ee.Image('LANDSAT/LT05/C01/T1_TOA/LT05_151036_19980608'); Map.addLayer(clipped1998,{ bands: ['B5', 'B4', 'B3'],},'1998'); Map.addLayer(clipped2017,{ bands: ['B6', 'B5', 'B4'],},'2017'); var newfc = water.merge(vege).merge(Builtup).merge(Barrenland); var training = clipped1998.select(bands).sampleRegions({collection: newfc,properties: ['landcover'], scale: 30}); var classifier = ee.Classifier.smileRandomForest(10).train({features: training, classProperty: 'landcover', inputProperties: bands});
```

$$P\ (X\ \geq xT) = \frac{1}{T} \qquad \text{(Eq. 2)}$$

Whereas: X is the intensity of one event (discharge of the stream/river); T is the duration (return period e.g, 5, 10, 50 & 100 yaers); and P is the probability of the event (maximum discharge of the stream/river)

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y} \qquad \text{(Eq. 3)}$$

Whereas: ρ Pearson Correlation Coefficient; σ is the standard deviation of; x is independent (population growth), and y is dependent variables (built-up area and permibility).

Based on the history of damages in these sites, the exposure and flood hazard are considered as a binary constant with the proximity of a 500-meter radius from torrents and/or drainage channels (Government of Khyber Pakhtunkhwa, 2016; Government of Pakistan, 2010; Khan et al., 2010; United Nations Development Programme, 2010). The inventory of the elements at risk is composed of housing and commercial and manufacturing units as well as all critical facilities, such as hospitals, schools, roads, bridges, etc. Each element at risk is quantified in terms of its importance and relationship with the urban floods. The literature review and the reports of NDMA and PDMA, KP are considered for indexing each element at risk. The Damages Need Assessment (DNA) report of the 2010 floods is taken as a base to validate the weightage of each element at risk in the index (Government of Khyber Pakhtunkhwa, 2016 and 2017; Government of Pakistan, 2010; United Nations Development Programme, 2010). This indexing assigns weightage for the multi-components of vulnerability, i.e., physical, economic, social, and attitudinal to each element at risk using a modified Fisher's Ideal Quantity index (mFIQI) (Eq. 4). The physical vulnerability of the physical infrastructure, i.e., houses; shops; critical facilities; water and sanitation (WATSAN); and drainage system are assessed through construction type, design, elevation (altitude), and structural mitigation measures. The economic vulnerability is assessed by estimating the cost of structural and non-structural damages; type of commercial activities; and indirect losses. The social and attitudinal vulnerabilities are determined by the level of preparedness for flood response; cohesion bond among neighborhood and business communities; community-based organizations (CBOs); and knowledge, perception, attitude, and practices regarding urban floods. The multi-components of vulnerability are combined into singular expressions for each element at risk by Eq. 02. The sector's wise vulnerability is determined by Patnaik & Narayan Vulnerability Index Formula (Eq. 5).

$$V = \sqrt{\frac{\sum Pnq_0}{\sum P0q_0} \times \frac{\sum Pnq_n}{\sum P0q_n}} \times 100 \qquad \text{(Eq. 4)}$$

Where q0 is the base value of vulnerability, which is considered a constant as 1; qn is an index and proportional value (Table 4); P0 is temporal changes in vulnerability, which are assumed to be constant as 1; therefore, it is equal to the base value; and Pn = data analysis value of the vulnerability.

$$VI = \left[\sum (AI_i)^a\right]^{I/a/n} \qquad \text{(Eq. 5)}$$

Where AI is the average vulnerability index of the variables (residential, commercial sector, and critical facilities); α is the variable; and n is the total no. of variables (in present study 5).

3. Results and Discussion

3.1. Urban Floods in Peshawar

Hydro-morphometric analysis at the regional level is carried out to understand the nature of flow, type of flood, and water availability in these streams. Based on this analysis, a detailed study of the hydro-morphometric system in the Peshawar district is conducted (Fig. 1). Although all watersheds are drained into River Kabul, for better understanding, the tributary watersheds are studied individually. The major river and streams along with their watersheds are Khazam Khwar, Budhni Nullah, River Bara, River Kabul, Zindai Khwar, Shafa Khana Khwar, and Chora Khwar. River Kabul has a very large covered watershed area. Based on Strahler stream order, shape, size, and slope analysis, it is oblivious that the flow in the river Kabul is perennial in nature. The covered area of the watershed of River Kabul in the district Peshawar is 137.05 km^2. The Irrigation Department, Peshawar calculated the flow discharge in the natural streams on a daily basis in the whole Peshawar district. The comparative summary of the fluvial floods of the last ten years is given in Figure 2. The flood frequency analysis for the major rivers and streams as well as their return period is calculated in Table 1 and presented in Figure 3.

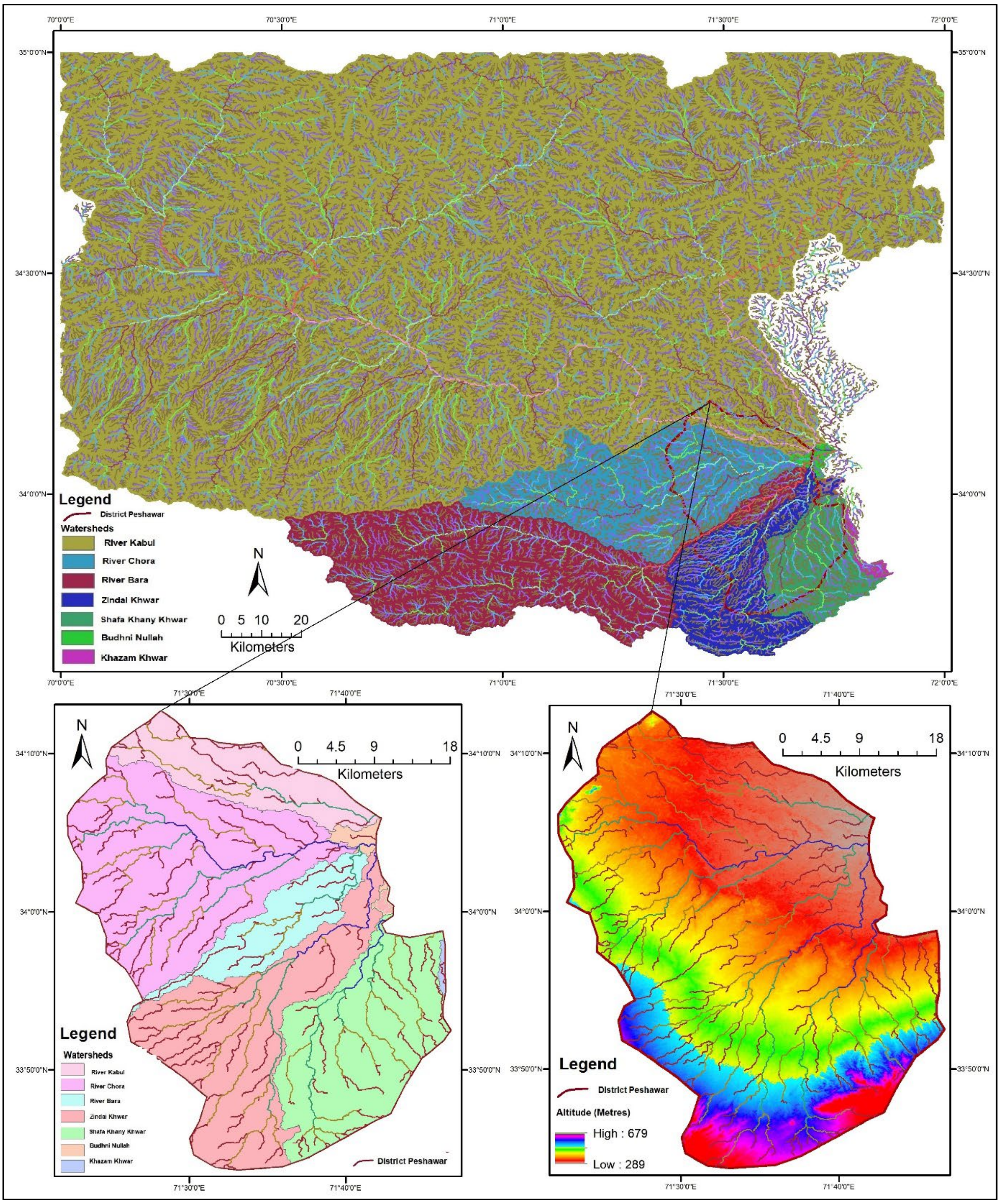

Figure 1. (a) Supported watersheds of all rivers and streams; (b) Watersheds and stream order analysis in district Peshawar; and (c) Slope and stream order Analysis in district Peshawar.

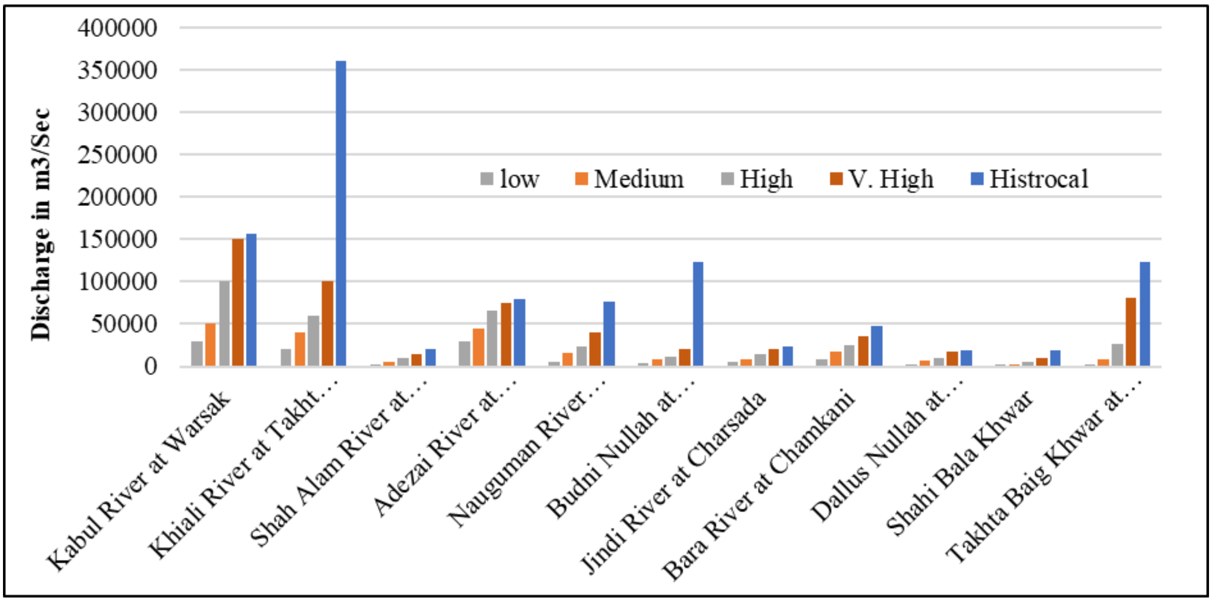

Figure 2. Summary of the fluvial floods and their discharge in district Peshawar.

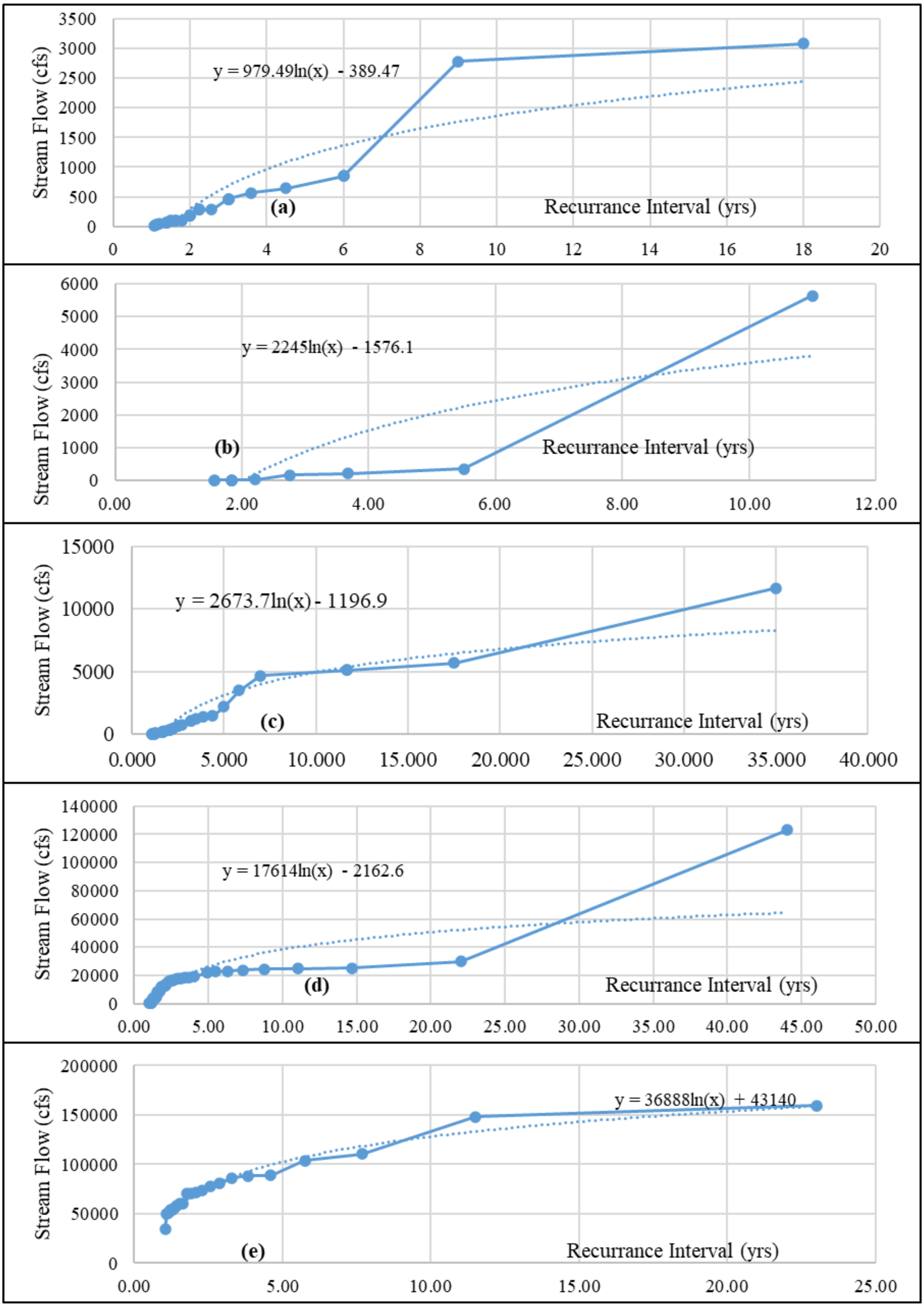

Figure 3. Flood frequency analysis of the major rivers in the district Peshawar; (a) Kabul River at Adezai Gauge Station; (b) Badaber Khwar at Kohat Road Gauge Station; (c) Bara River at Kohat Road Gauge Station; (d) Budni Nullah at Darmangi Gauge Station; (e) Kabul River at Warsak Dam Gauge Station.

Table 1. Flood Frequency Analysis of the Major Rivers in District Peshawar

Equation Constant Value	Return Period (Years)	LN	Max Discharge (Cusec) $P\ (X\ \geq xT) = \frac{1}{T}$
(a) Kabul River at Adezai Gauge Station			
24064	5	1.61	39844
24064	10	2.30	56524
24064	50	3.91	95254
24064	100	4.61	111934
(b) Badaber Khwar at Kohat Road Gauge Station			
233	5	1.61	236
233	10	2.30	398
233	50	3.91	772
233	100	4.61	934
(c) Bara River at Kohat Road Gauge Station			
3728	5	1.61	3630
3728	10	2.30	6214
3728	50	3.91	12213
3728	100	4.61	14797
(d) Budni Nullah at Darmangi Gauge Station			
30399	5	1.61	33633
30399	10	2.30	54704
30399	50	3.91	103630
30399	100	4.61	124701
(e) Kabul River at Warsak Dam Gauge Station			
44194	5	1.61	109579
44194	10	2.30	140212
44194	50	3.91	211340
44194	100	4.61	241973

Urban floods in Peshawar are primarily pluvial in nature because they mostly occur due to torrential heavy rainfall for a longer period of time (Fig. 4). However, floods were intensified by certain anthropogenic factors, such as population, urbanization, encroachment, failure of the drainage and sanitation system e.g., Shahi Katta drain in old city region. Urban floods were recorded in the years 2010, 2012, 2013, 2014, 2015, 2016, and 2017. The urban floods of 2012, 2013, and 2015 were associated with fluvial floods and poor drainage of the natural rivers and streams. The water was entered in urban areas due to blockage of the natural flow in the rivers and streams and/or water current was not able to join the main drainage drain in these areas. After these floods, the government paid attention to cleaning, widening, and de-siltation of the Budhni Nullah and its tributaries in the district Peshawar. Consequently, it minimized the risk of floods in these areas. However, the floods of 2015 and 2017 are purely associated with poor drainage and sanitation. The risk of urban flooding is further exacerbated by developmental activities of Bus Rapid Transit (BRT), Peshawar which directly blocked and/or minimize the capacity of old Shahi Katta and other drainage and sanitation drains in the areas. The urban flooding situation is further aggravated by issues related to cleanliness and improper solid waste management. With a dysfunctional and ancient drainage system like Shahi Kattha, the torrential rainfall just adds to the problems of the city's residents. This drain is 10 km long and 8 ft wide and is occupied by illegal constructions. It has become nearly impossible for the locals and the line agencies to clean it unless these illegal constructions are removed. Overflowing gutters, flooding of transportation routes, and closing down of commercial areas are just a few of the main problems that are faced by the locals. Looking at developmental activities, encroachments coupled with poor planning regarding exacerbating the risk of urban floods in Peshawar. Besides, the primary cause of rainfall, the other intensified factors are urban growth, irrigation systems, solid waste management, drainage and sanitation system, and permeability.

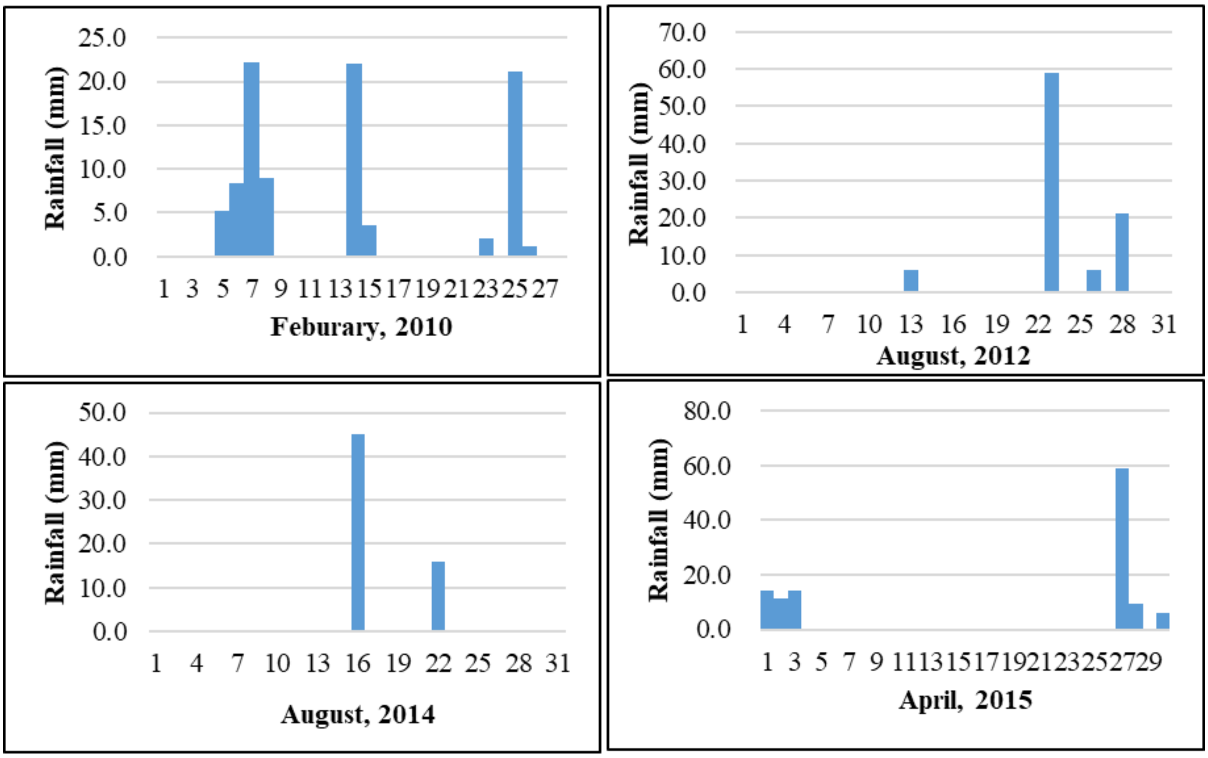

Figure 4 The amount of rainfall in major historical flash flood events (i.e., 2010, 2012, 2014, and 2015) in Peshawar.

3.2. The Nexus of Urban Development and Urban Floods

Urban growth seriously affected the hydrological system, including water usage, water permeability, water table, etc., which intensified the urban flood conditions in this region. In the last twenty years, the land use analysis shows that the built-up area is more than doubled with population growth and urbanization pace (Figure 5). Including the Afghan refugee population, the population of the district Peshawar is increasing with a terrific rate of 4% annual growth rate. This is the highest growth rate elsewhere in the country (Government of Pakistan, 1999, 2017 and 2018). This rapid increase in population has severally affected the utilities and services in the city area, particularly the housing, sanitation, drainage, water supply, and recreation facilities. This pressure leads to encroachments, blockage of the sewerage system, and depletion of the water table. The multi-purpose Warsak Dam is constructed on River Kabul at the entrance to the district Peshawar. The network of irrigation perpendicularly crosses the drainage system. Consequently, it is always the source of blockage and works as an intensifying factor for floods. Similarly, the furrow in the fields is always resisted by the natural flow in the fields. The existing sanitation/stormwater systems are a combination of all sorts of water collection of domestic, commercial, and industrial wastewater along with surface runoffs during urban floods. The flows are mostly conveyed by open or covered drains. The analysis of the permeability of water and the built-up (impervious) area is very important for understanding the causes of urban floods and drought. The surface discharge is directly dependent on the permeability of water and the covered area. Floods are dependent on surface water discharge. The analysis shows that the total area for the permeability of water has decreased in Peshawar. The total area included vegetation, water, and barren land uses (Table 2). The population growth and built-up area have a perfect positive (+1) correlation, while the population growth and permeability have a perfect negative (-1) correlation.

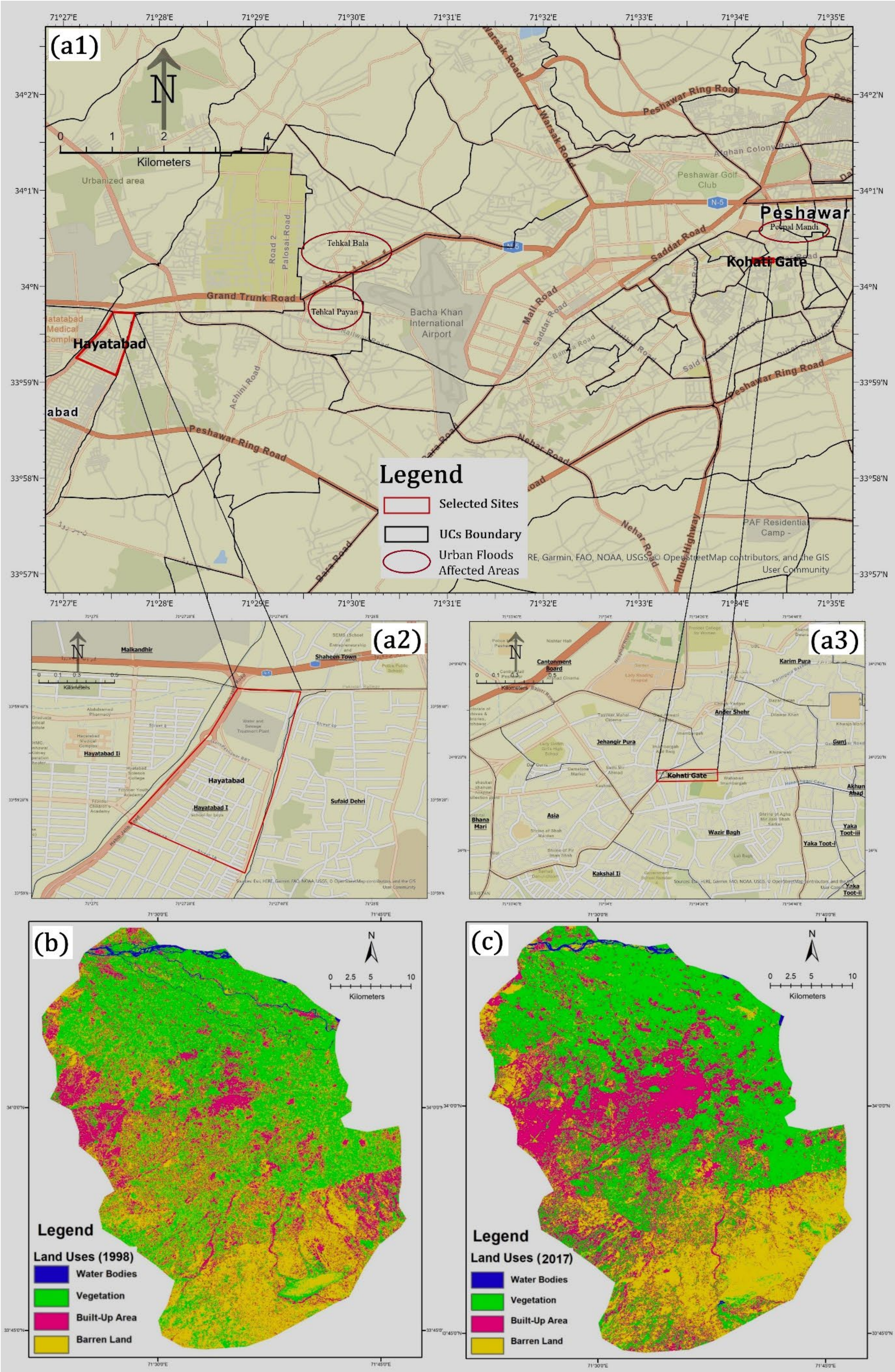
(a1)
Peshawar
Tehkal Bala
Tehkal Payan
Hayatabad
Kohati Gate
Peepal Mandi
Bacha Khan International Airport
Grand Trunk Road
Peshawar Ring Road
Legend
Selected Sites
UCs Boundary
Urban Floods Affected Areas
(a2)
(a3)
(b)
Legend
Land Uses (1998)
Water Bodies
Vegetation
Built-Up Area
Barren Land
(c)
Legend
Land Uses (2017)
Water Bodies
Vegetation
Built-Up Area
Barren Land

Figure 5. (a1, 2 and 3) Selected Sample Sites; (b) Land use in district Peshawar, 1998; (c) Land use in district Peshawar, 2017.

Table 2. Permeability of water in district Peshawar

S N	**Indicators**	**1998**	**2017**	**Change**	**Relative Change (%)**	**Corelation** $\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$
1	Population (Persons)	2026851	4269079	2242228	110.63	population growth (1) and built-up area (2) = +1
2	Built-up Area (Km2)	137	352.62	215.62	157.39	
3	Barren Land (Km2)	696.35	358	-338.35	-48.59	population growth (1) and permeability (6) = -1
4	Vegetation (Km2)	411	540	129	31.39	
5	Water (Km2)	13.1	6.38	-6.27	-47.86	
6	3+4+5	1120.45	904.83	-215.62	-19.24	

3.3. Quantitative Vulnerability Index

Based on the literature review and field data regarding the impacts of past urban floods, a quantitative vulnerability index of the elements at risk is constructed. The specific weightage for the component of the vulnerability is calculated on the average value of historical and field data, which is rectified with the damages need assessment report of floods–2010 (Government of Khyber Pakhtunkhwa, 2016, 2017; Government of Pakistan, 2010). This specific weightage is assigned to each of the elements at risk. The index value of this weightage is normalized from 0 to 1 for each element at risk. Furthermore, the available literature is thoroughly studied to ensure the accuracy of the index (Table 3). Only the fluvial nature of the floods is reported in the historical data on floods. In the case of households, human deaths and economic damages are associated with physical damage. In the case of commercial and manufacturing, people were able to evacuate with their precious items. Economic damages are associated with the level of flood inundation. The cost of physical damages to critical facilities with service interruption leads to economic damages. The evacuation and adaptation to the risk of floods are dependent on social & attitudinal vulnerability, which are mostly associated with private ownership. For example, the 2016 urban floods have a higher contribution to the economic component of vulnerability; therefore, a higher weightage of 0.6 will be given to economic vulnerability, followed by 0.3 to the physical component and 0.1 to each social and attitudinal vulnerability.

In terms of vulnerability components, the index is based on the contribution of the impacts of previous urban floods on the physical, economic, social, and attitudinal aspects. The coded and univariate analysis data of the desired section of the component of vulnerability from the interviews are assembled. Each section of housing, commercial, and critical facilities is associated with its physical, economic, social, and attitudinal vulnerabilities. The results of different participants show very high coherence among their responses for different categories. In SPSS, the responses and/or scores of the multi-component of vulnerability and sector are compared to find out the association in all data sets. Almost, all of the responses have lesser or smaller values than 0.05, which shows strong associations among the results. The average result of the four datasets, i.e., impacts of floods, interviews, questionnaires, and field observations shows the singular expression of the multi-component of vulnerability in each sector.

The sector-wise vulnerability is divided into three major sectors, i.e., the housing sector, commercial sector, and critical facilities. The vulnerability index value of each vulnerability component is different for targeted sectors. In terms of the vulnerability index of the residential sector, the physical conditions of a household/commercial unit were linked with their contributions to inflicting physical and economic damages in the past. These components are analyzed by associating the impacts with vulnerability indicators in terms of urban flood impact on them or the contribution of these indicators in increasing or decreasing the damageability of these floods. For example, a house made of waterproof construction material will significantly lower the damageability of urban floods, hence lowering the physical vulnerability of that house. Similarly, a commercial unit that is elevated a few feet from the ground will have lower physical and economic vulnerability as the flood water won't be able to enter that unit. Similarly, factors such as dependency, social cohesion, and behavioral changes before and after a flood were linked with the probable damages to know about the vulnerability index of the residential sector. The vulnerability index of the housing sector is based on factors such as type of house, altitude, and mitigation measures. The average weightage values of 0.6, 0.2, and 0.2 are assigned to physical, economic, and social & attitudinal, respectively.

The vulnerability index of the commercial sector was determined by associating the frequency and damages of past urban floods and their contribution to elements at risk such as inflation, investment patterns, and type of economic activities. The social and attitudinal vulnerability of the commercial sector was determined by observing the structural and non-structural measures. The commercial and manufacturing sectors are largely based on the type of economic activity and investment patterns as well as market trends. Physical, social, and attitudinal play a role during emergencies. Based on the combined score of four datasets, the average weightage values of 0.1, 0.7, and 0.2 are assigned to physical, economic, and social and attitudinal vulnerabilities, respectively. Similarly, the vulnerability index of critical facilities was determined by associating the damages of past urban floods to these facilities and secondary and indirect damages caused by them in relief and rehabilitation efforts and to commercial units. The role of critical facilities during emergencies and their contribution to indirect economic losses are very important variables in the quantification of their physical, economic, and social and attitudinal vulnerabilities. These variables are analyzed in the four datasets and their results are converted to average weightage values. The average weightage values of 0.6, 0.3, and 0.1 are assigned to physical, economic, and social & attitudinal, respectively (Table 4).

Table 3. Summary of the impacts of urban floods in district Peshawar

Urban Floods	Location	Impacts
2016	Batta Thal bridge, near the Bara torrent	70 shops were destroyed with damages to several other shops
2015	Budhni Nullah	34 deaths, evacuation of 300 residents, and massive damage to the residential & commercial properties
2013	Hayatabad, Charsadda Road, Nasir Bagh and Warsak Road	2 dead, 4 were injured, 17 shops were destroyed, and inundation of transportation routes
2012	Bara Road, Gulberg, Nauthia, Landi Arbab, Saddar, Tehkal, Charsadda Road, Kohati Gate, Qissa Khawani, Khyber Road	600 million PKR worth of damage was caused to commercial units in the Saddar area alone. Dozens of houses were caved in, becoming inhabitable
2010	Almost the entire of Peshawar city was affected in one form or another.	33,867 households were affected and 5406 livestock deaths. The total number of people affected was 237,068

Table 4. Sector-wise quantitative multi-components vulnerability index (Normalised score)

Component of Vulnerability	Impacts of Floods	Interviews	Questionnaires	Field's Observations	Average Score
Housing					
Physical	0.6	0.6	0.6	0.6	**0.60**
Economic	0.3	0.2	0.2	0.1	**0.20**
Social and Attitudinal	0.1	0.2	0.2	0.3	**0.20**
Commercial & Manufacturing					
Physical	0.1	0.2	0.1	0.2	**0.13**
Economic	0.7	0.7	0.7	0.5	**0.65**
Social and Attitudinal	0.2	0.1	0.2	0.3	**0.20**
Critical Facilities					
Physical	0.7	0.5	0.5	0.7	**0.60**
Economic	0.2	0.4	0.4	0.2	**0.30**
Social and Attitudinal	0.1	0.1	0.1	0.1	**0.10**

3.4. Assessment of the Multi-components of Vulnerability

Vulnerability has different dimensions, i.e., physical, economic, social and attitudinal, which are assessed individually and then converted to a singular form of vulnerability. The housing, commercial and manufacturing, and critical facilities had different weightage values as well as assessment variables for the multi-components of the vulnerability. The values of all variables are normalized and the normalized average value considered all variables with equal weightage. In the housing sector, the physical vulnerability is assessed through house design, elevation (m), and flood-proofing of housing; the commercial vulnerabilities in terms of the cost of structural and non-structural damages to the houses; cohesion bond in the family, self-help and trust-based system in the community; and role of the CBOs, are the indicators for the social vulnerability assessment; while the attitudinal vulnerability is assessed by knowledge regarding urban floods, perception about urban flooding and practices during urban flooding (Table 5).

The components of physical vulnerability in the commercial & manufacturing sector are assessed through variables of location/distance (m), construction type, elevation (m), and flood-proofing; and worth of structural and non-structural damages, the type of economic activity and hierarchy/assets value are the components of economic vulnerability, while the level of preparedness and role of CBOs during emergencies; and knowledge regarding urban floods, perception about urban flooding and practices during urban flooding are considered the key components of social and attitudinal vulnerability (Table 6). In case of a flood event, the probable monetary damages to the houses and commercial units and their contents are calculated. All of this monetary damage was assessed in PKR. If the damage was between 10000 PKR in a flood event, then the damage was classified as '1' indicating a low level of vulnerability. If it was up to 15000 PKR then the damage was classified as 2, indicating the medium level of vulnerability. If it was above 15000 PKR then the vulnerability was classified as high level. The critical facilities have components of three types of vulnerability (i.e., physical, economic, and social) with no attitudinal component, which is assessed through location/ distance (m), elevation (m), and flood-proofing; structural & non-structural damages; and accessibility, capability, and critical role during floods, respectively (Table 7).

Table 5. Normalized values of the multi-components of the vulnerability of the housing sector

Hayatabad: Physical Vulnerability						Hayatabad: Economic Vulnerability		
Household ID	House Type	House Design	Elevation (m)	Flood Proofing	Normalized Average Value	Structural Damages	Non-Structural Damages	Normalized Average Value
1	0.1	0.5	0.36	0.1	0.49	0.5	0.1	0.3
2	0.1	0.1	0.36	0.1	0.39	0.3	0.1	0.2
3	0.1	0.5	0.36	0.5	0.59	0.7	0.1	0.4
…								
50	0.1	0.9	0.36	0.1	0.59	0.1	1	0.55
Kohati Gate: Physical Vulnerability						Kohati Gate: Economic Vulnerability		
1	0.54	0.1	0.36	0.5	0.37	0.1	0.63	0.36
2	0.99	0.1	0.63	0.5	0.55	0.1	0.47	0.28
3	0.1	0.1	0.36	0.5	0.26	0.1	0.42	0.26
…								
25	0.1	0.1	0.36	0.9	0.36	0.1	0.1	0.1
Hayatabad: Social Vulnerability					Hayatabad: Attitudinal Vulnerability			
Household ID	Cohesion Bond	Self-Help & Trust-Based System	CBOs	Normalized Average Value	Household ID	Knowledge	Perception	Practices
1	0.9	0.63	0.9	0.81	0.36	0.1	0.23	0.23
2	0.9	0.63	0.9	0.81	0.63	0.63	0.63	0.63
3	0.9	0.63	0.9	0.81	0.1	0.1	0.1	0.1
…								
50	0.1	0.36	0.63	0.36	0.1	0.1	0.1	0.1
Kohati Gate: Social Vulnerability					Kohati Gate: Attitudinal Vulnerability			
1	0.9	0.36	0.1	0.45	0.36	0.1	0.23	0.23
2	0.9	0.1	0.36	0.45	0.1	0.36	0.23	0.23
3	0.9	0.1	0.36	0.45	0.1	0.36	0.23	0.23
…								
25	0.1	0.63	0.9	0.54	0.9	0.63	0.76	0.76

Table 6. Normalized values of the multi-components of the vulnerability of the commercial sector, Kohati Gate

Physical Vulnerability						Economic Vulnerability					Social Vulnerability			Attitudinal Vulnerability			
Unit ID	Location / Distance (m)	Construction Type	Elevation (m)	Flood Proofing	Normalized Average Value	Structural Damages	Non-Structural Damages	Type of Economic Activity	Hierarchy / Assets Value	Normalized Average Value	Level of Preparedness	CBOs	Normalized Average Value	Knowledge	Perception	Practices	Normalized Average
1	0.8	0.1	0.5	0.4	0.4	0.3	0.5	0.1	0.9	0.4	0.9	0.3	0.6	0.1	0.1	0.1	0.1
2	1.0	0.1	0.5	0.4	0.5	0.6	0.6	0.1	0.9	0.6	0.9	0.3	0.6	0.1	0.1	0.1	0.1
3	1.0	0.1	0.5	0.9	0.6	0.5	0.7	0.4	0.9	0.6	0.6	0.4	0.5	0.1	0.1	0.1	0.1
…																	
50	0.4	0.1	0.5	0.1	0.3	0.6	0.8	0.4	0.5	0.7	0.3	0.3	0.3	0.1	0.1	0.1	0.1

Table 7. Normalized values of the multi-components of the vulnerability of critical facilities

Unit ID	Physical Vulnerability				Economic Vulnerability			Social Vulnerability			
	Location / Distance (m)	Elevation (m)	Flood Proofing	Normalized Average Value	Structural Damages	Non-Structural Damages	Normalized Average Value	Accessibility	Capability	Critical Role	Normalized Average Value
	Hayatabad										
1	0.2	0.1	0.5	0.3	0.3	0.5	0.4	0.1	0.5	0.5	0.4
2	1.0	0.7	0.9	0.9	0.2	0.2	0.2	0.1	0.9	0.1	0.4
3	0.3	0.5	0.5	0.4	0.9	0.3	0.6	0.5	0.1	0.5	0.4
4	0.1	0.5	0.1	0.2	0.3	0.6	0.4	0.1	0.1	0.1	0.1
5	1.0	0.7	0.9	0.9	0.6	0.7	0.7	0.1	0.5	0.9	0.5
6	1.0	0.7	0.9	0.9	0.1	0.4	0.2	0.9	0.1	0.1	0.4
	Kohati Gate										
1	0.9	0.6	0.9	0.8	0.4	0.2	0.3	0.1	0.1	0.5	0.2
2	0.9	0.1	0.9	0.6	0.6	0.1	0.4	0.5	0.1	0.1	0.2
3	0.9	0.1	0.9	0.6	0.2	0.2	0.2	0.1	0.9	0.9	0.6
4	0.1	0.6	0.9	0.5	0.2	0.1	0.2	0.5	0.1	0.5	0.4
5	0.8	0.6	0.5	0.6	0.1	0.1	0.1	0.5	0.1	0.5	0.4
6	0.9	0.4	0.9	0.7	0.9	0.2	0.5	0.9	0.1	0.9	0.6

3.5. Generalized Sector Wise Vulnerability Index

The elements at risk are grouped into sectors of households, commercial and manufacturing units, and critical facilities. The multi-components of vulnerability are assigned with the Quantitative Vulnerability Index values and their impacts are combined into a singular expression of vulnerability using Equation 4. In the Hayatabad region, the results of the multi-components of vulnerability for 75 sample households and all six critical facilities in the buffer zone of a 500-meter radius from torrents are included with no commercial activities in the targeted areas. Similarly, the results of 25 households, 50 commercial & manufacturing units, and all six critical facilities in the buffer zone of Kohati Gate are calculated. The list of critical facilities in the Hayatabad region are 2 bridges, 2 roads, 1 University, and 1 recreational park while in the Kohati Gate region are 2 bridges; 2 roads/streets; and 2 Schools. Based on Equation 3 calculations, the q_n represents the weightage and/or index value and p_n represents the observed field value, while the expected changes in the observed period of time in these values of p_0 & q_0 are considered as constant for each element at risk in all components of vulnerability (Table 8). The physical and economic vulnerability is much higher in the Kohati Gate region while social vulnerability is comparatively higher in the Hayatabad region. The attitudinal is almost the same with higher awareness and a low score of vulnerability.

The generalized sector-wise vulnerability index for both regions of Hayatabad and Kohati Gate is calculated by Equation 5. In this process, the average singular expression of the vulnerability of all elements at risk in the three selected sectors is calculated and then divided by the total number of vulnerabilities (sources and/or the number of observations). In both regions, each sector is ranked based on its calculated value. In the Hayatabad region, the residential units are higher vulnerable than critical facilities with low average values of 0.30 and 0.26, respectively. The lower values indicate better DRR measures for urban floods in this region. In Gohati Gate, the average index values for commercial, critical facilities, and residential sectors are 0.41, 0.28, and 0.20, respectively, reflecting very high vulnerability. The poor accessibility, old building structures, and incapacitated drainage system make the Kohati Gate region highly vulnerable to urban floods. The high values of economic losses as well as poor physical infrastructure in the Kohati Gate areas keep the commercial sector at the first rank in the overall generalized sector-wise index of the vulnerability to urban floods (Table 9).

Table 8. Quantification of the multi-components of vulnerability

Unit ID	Vulnerability	q_n	q_0	p_0	p_n	p_nq_0	p_nq_n	p_0q_n	p_0q_0
Housing Sector in the Hayatabad									
1	Physical	0.60	1	1	0.49	0.49	0.29	0.60	1
	Economic	0.20	1	1	0.30	0.30	0.06	0.20	1
	Social	0.10	1	1	0.81	0.81	0.08	0.10	1
	Attitudinal	0.10	1	1	0.23	0.23	0.02	0.10	1
	Total	1	4	4	1.83	1.83	0.45	1	4
$\sum(p_nq_0)/\sum(p_0q_0) = 0.45$; $(\sum p_nq_n)/(\sum p_0q_n) = 0.45$; and $\sqrt{(\sum p_nq_0/\sum p_0q_0)\times(\sum p_nq_n/\sum p_0q_n)} = 0.30$									
…									
50	Physical	0.60	1	1	0.36	0.36	0.21	0.60	1
	Economic	0.20	1	1	0.10	0.10	0.02	0.20	1
	Social	0.10	1	1	0.10	0.10	0.01	0.10	1
	Attitudinal	0.10	1	1	0.76	0.76	0.07	0.10	1
	Total	1	4	4	1.32	1.32	0.32	4	4
$\sum(p_nq_0)/\sum(p_0q_0) = 0.33$; $(\sum p_nq_n)/(\sum p_0q_n) = 0.08$; and $\sqrt{(\sum p_nq_0/\sum p_0q_0)\times(\sum p_nq_n/\sum p_0q_n)} = 0.04$									
Commercial Sector in the Kohati Gate									
1	Physical	0.10	1	1	0.43	0.43	0.04	0.10	1
	Economic	0.70	1	1	0.40	0.40	0.28	0.70	1
	Social	0.10	1	1	0.63	0.63	0.06	0.10	1
	Attitudinal	0.10	1	1	0.10	0.10	0.01	0.10	1
	Total	1	4	4	1.56	1.56	0.39	1	4
$\sum(p_nq_0)/\sum(p_0q_0) = 0.39$; $(\sum p_nq_n)/(\sum p_0q_n) = 0.39$; and $\sqrt{(\sum p_nq_0/\sum p_0q_0)\times(\sum p_nq_n/\sum p_0q_n)} = 0.24$									
…									
50	Physical	0.10	1	1	0.26	0.26	0.02	0.10	1
	Economic	0.70	1	1	0.74	0.74	0.51	0.70	1
	Social	0.10	1	1	0.32	0.32	0.03	0.10	1
	Attitudinal	0.10	1	1	0.10	0.10	0.01	0.10	1
	Total	1	4	4	1.42	1.42	0.58	4	4
$\sum(p_nq_0)/\sum(p_0q_0) = 0.30$; $(\sum p_nq_n)/(\sum p_0q_n) = 0.14$; and $\sqrt{(\sum p_nq_0/\sum p_0q_0)\times(\sum p_nq_n/\sum p_0q_n)} = 0.08$									
Critical Facilities in the Hayatabad and Kohati Gate Region									
1	Physical	0.60	1	1	0.26	0.26	0.15	0.60	1
	Economic	0.20	1	1	0.38	0.38	0.07	0.20	1
	Social	0.10	1	1	0.36	0.36	0.03	0.10	1
	Attitudinal	0.10	1	1	0	0	0	0.10	1
	Total	1	4	4	1	1	0.26	1	4
$\sum(p_nq_0)/\sum(p_0q_0) = 0.25$; $(\sum p_nq_n)/(\sum p_0q_n) = 0.26$; and $\sqrt{(\sum p_nq_0/\sum p_0q_0)\times(\sum p_nq_n/\sum p_0q_n)} = 0.13$									

…									
12	Physical	0.60	1	1	0.72	0.72	0.43	0.60	1
	Economic	0.20	1	1	0.53	0.53	0.10	0.20	1
	Social	0.10	1	1	0.63	0.63	0.06	0.10	1
	Attitudinal	0.10	1	1	0	0	0	0.10	1
	Total	1	4	4	1.88	1.88	0.60	4	4
$\sum(p_n q_0)/\sum(p_0 q_0) = 0.47$; $(\sum p_n q_n)/(\sum p_0 q_n) = 0.15$; and $\sqrt{(\sum p_n q_0 / \sum p_0 q_0) \times (\sum p_n q_n / \sum p_0 q_n)} = 0.10$									

Table 9 Generalized vulnerability index of Hayatabad and Kohati Gate

Region	Sector Type	Average Index	Generalized Value	Rank $VI = [\sum(AI_i)^a]^{I/a}/n$
Kohati Gate	Commercial Sector	0.41	0.02	1
Hayatabad	Residential Sector	0.30	0.02	2
Kohati Gate	Critical Facilities	0.28	0.01	3
Hayatabad	Critical Facilities	0.26	0.01	4
Kohati Gate	Residential Sector	0.20	0.01	5

4. Conclusions

All DRR activities are directly dependent on disaster risk assessment. Hazard, exposure, vulnerability & capacity are the major components of the process of disaster risk assessment. In the present study, hazard and exposure were considered as a binary constant and all elements at risk in the proximity of 500 meters from torrents and drainage systems were considered to be equally exposed to the same magnitude of flood. This study was focused on the assessment of multi-components and sector-wise vulnerability to urban floods in Peshawar – Pakistan. The inventory of the elements at risk was grouped into three major sectors of residential, commercial & manufacturing, and critical facilities. The sample sites of residential and commercial areas were selected from the most affected areas of Peshawar due to urban flooding. In the Hayatabad region, the predominant activities were residential, and the nature of the flood was fluvial, while in the Kohati Gate area, the predominant activities were commercial and manufacturing, and urban flooding was caused by the poor drainage system.

Each element at risk was geo-spatially coded in its specific region. The official records of floods were considered for indexing the worth of each element at risk. Based on the historical data as well as field observations and literature review, an index of weightage for the different sectors in the vulnerability was prepared. The multi-components of vulnerability were assessed for all elements at risk and results were normalized. These multi-components of vulnerability were converted to average value with the assigned index weightage value. Using the mFIQI equation, the multi-components of the vulnerability of all elements at risk were converted to singular expressions of vulnerability. The generalized vulnerability index of Hayatabad and Kohati Gate was prepared and was generalized, simultaneously. The old physical infrastructure of commercial and manufacturing units in the Kohati Gate area made it highly vulnerable to urban floods, while the residential units were located at a distance from the drainage system made it less susceptible to urban floods. Whereas, in Hayatabad, the encroachments along the torrent's sides of housing as well as educational institutions contributed to higher vulnerability to urban floods, although the physical vulnerability was the lowest observed in these elements at risk. The most important aspects of this study were the singular expression of the multi-components of vulnerability and the adaptability of a new approach for any other geo-spatial or statistical technique of vulnerability assessment. Risk-informed development is the cross-cutting theme of Sustainable Development Goals (SDGs), which can be achieved through disaster risk assessment. Ultimately, this study will provide a platform for risk assessment and precise data for DRR of urban floods. The assessment of multi-components of vulnerability and its sector-wise ranking provides practical information during planning and plan preparation for disaster managers and urban planners. A regional-based generalized index for the weightage of component vulnerability and the use of AI will enhance the application of this tool to different flooding scenarios.

Acknowledgment

The authors would like to thank the National Disaster Management Authority (NDMA), Pakistan, Provincial Disaster Management Authority-Khyber Pakhtunkhwa (PMDA-KP), Pakistan Meteorological Department (PMD), and Provincial Irrigation Department for providing us with the relevant data. The authors acknowledge Rabdan Academy, United Arab Emirates (UAE) for supporting Article Processing Charges (APC). The authors also acknowledge the United States Geological Survey (USGS) for the ASTER DEM images.

References

Abbas, A., Ullah, S., Ullah, W., Zhao, C., Karim, A., Waseem, M., Bhatti, A.S., Ali, G., Jan, M.A., Ali, A., 2023. Characteristics of Winter Precipitation over Pakistan and Possible Causes during 1981–2018. Water (Basel) 15, 2420. https://doi.org/10.3390/w15132420

Abebe, Y., Kabir, G., Tesfamariam, S., 2018. Assessing urban areas vulnerability to pluvial flooding using GIS applications and Bayesian Belief Network model. J Clean Prod 174, 1629–1641. https://doi.org/10.1016/j.jclepro.2017.11.066

Aerts, J.C.J.H., Botzen, W.J., Clarke, K.C., Cutter, S.L., Hall, J.W., Merz, B., Michel-Kerjan, E., Mysiak, J., Surminski, S., Kunreuther, H., 2018. Integrating human behaviour dynamics into flood disaster risk assessment. Nat Clim Chang 8, 193–199. https://doi.org/10.1038/s41558-018-0085-1

Berman, E., 2017. An Exploratory Sequential Mixed Methods Approach to Understanding Researchers' Data Management Practices at UVM: Integrated Findings to Develop Research Data Services. J Escience Librariansh 6, e1104. https://doi.org/10.7191/jeslib.2017.1104

Berndtsson, R., Becker, P., Persson, A., Aspegren, H., Haghighatafshar, S., Jönsson, K., Larsson, R., Mobini, S., Mottaghi, M., Nilsson, J., Nordström, J., Pilesjö, P., Scholz, M., Sternudd, C., Sörensen, J., Tussupova, K., 2019. Drivers of changing urban flood risk: A framework for action. J Environ Manage 240, 47–56. https://doi.org/10.1016/j.jenvman.2019.03.094

Bhat, M.S., Alam, A., Ahmad, B., Kotlia, B.S., Farooq, H., Taloor, A.K., Ahmad, S., 2019. Flood frequency analysis of river Jhelum in Kashmir basin. Quaternary International 507, 288–294. https://doi.org/10.1016/j.quaint.2018.09.039

Biswas, S., 2023. A review of socio-economic vulnerability: The emergence of its theoretical concepts, models and methodologies. Natural Hazards Research. https://doi.org/10.1016/j.nhres.2023.05.005

Chen, Y., Zhou, H., Zhang, H., Du, G., Zhou, J., 2015. Urban flood risk warning under rapid urbanization. Environ Res 139, 3–10. https://doi.org/10.1016/j.envres.2015.02.028

de Almeida, G.A.M., Bates, P., Ozdemir, H., 2018. Modelling urban floods at submetre resolution: challenges or opportunities for flood risk management? J Flood Risk Manag 11, S855–S865. https://doi.org/10.1111/jfr3.12276

Echendu, A.J., 2023. Applicability of Indigenous knowledge and methods in flood risk management in a nigerian city. Natural Hazards Research. https://doi.org/10.1016/j.nhres.2023.09.001

Erena, S.H., Worku, H., 2019. Urban flood vulnerability assessments: the case of Dire Dawa city, Ethiopia. Natural Hazards 97, 495–516. https://doi.org/10.1007/s11069-019-03654-9

Gall, M., Nguyen, K.H., Cutter, S.L., 2015. Integrated research on disaster risk: Is it really integrated? International Journal of Disaster Risk Reduction 12, 255–267. https://doi.org/10.1016/j.ijdrr.2015.01.010

Government of Khyber Pakhtunkhwa, 2021. Government of Khyber Pakhtunkhwa, Irrigation Department KPK [WWW Document].

Government of Khyber Pakhtunkhwa, 2016. Overview of Disasters in Khyber Pakhtunkhwa 2016 - Impact, Response and Managing Risks. Peshawar.

Government of Khyber Pakhtunkhwa, P.D.M.A., 2017. Annual Report 2017. Peshawar.

Government of Pakistan, 2021. Government of Pakistan, Khyber Pukhtunkhwa Weather Data, Regional Meteorological Center [WWW Document].

Government of Pakistan, 2010. Pakistan Floods 2010: Preliminary Damage and Needs Assessment - Pakistan. Islamabad.

Güneralp, B., Güneralp, İ., Liu, Y., 2015. Changing global patterns of urban exposure to flood and drought hazards. Global Environmental Change 31, 217–225. https://doi.org/10.1016/j.gloenvcha.2015.01.002

Hamidi, A.R., Wang, J., Guo, S., Zeng, Z., 2020. Flood vulnerability assessment using MOVE framework: a case study of the northern part of district Peshawar, Pakistan. Natural Hazards 101, 385–408. https://doi.org/10.1007/s11069-020-03878-0

Hammond, M.J., Chen, A.S., Djordjević, S., Butler, D., Mark, O., 2015. Urban flood impact assessment: A state-of-the-art review. Urban Water J 12, 14–29. https://doi.org/10.1080/1573062X.2013.857421

Hussain, M., Tayyab, M., Ullah, K., Ullah, S., Rahman, Z.U., Zhang, J., Al-Shaibah, B., 2023. Development of a new integrated flood resilience model using machine learning with GIS-based multi-criteria decision analysis. Urban Clim 50, 101589. https://doi.org/10.1016/j.uclim.2023.101589

Hussain, M., Tayyab, M., Zhang, J., Shah, A.A., Ullah, K., Mehmood, U., Al-Shaibah, B., 2021. GIS-Based Multi-Criteria Approach for Flood Vulnerability Assessment and Mapping in District Shangla: Khyber Pakhtunkhwa, Pakistan. Sustainability 13, 3126. https://doi.org/10.3390/su13063126

Ikram, Q.D., Jamalzi, A.R., Hamidi, A.R., Ullah, I., Shahab, M., 2023. Flood risk assessment of the population in Afghanistan: A spatial analysis of hazard, exposure, and vulnerability. Natural Hazards Research. https://doi.org/10.1016/j.nhres.2023.09.006

Jamali, B., Löwe, R., Bach, P.M., Urich, C., Arnbjerg-Nielsen, K., Deletic, A., 2018. A rapid urban flood inundation and damage assessment model. J Hydrol (Amst) 564, 1085–1098. https://doi.org/10.1016/j.jhydrol.2018.07.064

Khan, A.N., Khan, S.N., Ali, A., 2010. Analysis of damages caused by flood-2010 in district Peshawar. J. Sc. Tech. Univ. Peshawar 36, 11–16.

Khan, I., Ali, A., Waqas, T., Ullah, Sami, Ullah, Safi, Shah, A.A., Imran, S., 2022. Investing in disaster relief and recovery: A reactive approach of disaster management in Pakistan. International Journal of Disaster Risk Reduction 75, 102975. https://doi.org/10.1016/j.ijdrr.2022.102975

Khan, I., Waqas, T., Samiullah, Ullah, S., 2020. Precipitation variability and its trend detection for monitoring of drought hazard in northern mountainous region of Pakistan. Arabian Journal of Geosciences 13, 698. https://doi.org/10.1007/s12517-020-05700-4

Kumar, R., Karabenick, S.A., Warnke, J.H., Hany, S., Seay, N., 2019. Culturally Inclusive and Responsive Curricular Learning Environments (CIRCLEs): An exploratory sequential mixed-methods approach. Contemp Educ Psychol 57, 87–105. https://doi.org/10.1016/j.cedpsych.2018.10.005

Müller, A., Reiter, J., Weiland, U., 2011. Assessment of urban vulnerability towards floods using an indicator-based approach – a case study for Santiago de Chile. Natural Hazards and Earth System Sciences 11, 2107–2123. https://doi.org/10.5194/nhess-11-2107-2011

O'Donnell, E.C., Thorne, C.R., 2020. Drivers of future urban flood risk. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 378, 20190216. https://doi.org/10.1098/rsta.2019.0216

Osti, R., Nakasu, T., 2016. Lessons learned from southern and eastern Asian urban floods: from a local perspective. J Flood Risk Manag 9, 22–35. https://doi.org/10.1111/jfr3.12107

Ouma, Y., Tateishi, R., 2014. Urban Flood Vulnerability and Risk Mapping Using Integrated Multi-Parametric AHP and GIS: Methodological Overview and Case Study Assessment. Water (Basel) 6, 1515–1545. https://doi.org/10.3390/w6061515

Patnaik, U., Narayanan, K., 2009. Vulnerability and Climate Change: An Analysis of the Eastern Coastal Districts of India. Munich Personal RePEc Archive 1–20.

Rahman, A.S., Rahman, A., Zaman, M.A., Haddad, K., Ahsan, A., Imteaz, M., 2013. A study on selection of probability distributions for at-site flood frequency analysis in Australia. Natural Hazards 69, 1803–1813. https://doi.org/10.1007/s11069-013-0775-y

Rahman, A.U., Khan, A.N., 2013. Analysis of 2010-flood causes, nature and magnitude in the Khyber Pakhtunkhwa, Pakistan. Natural Hazards 66, 887–904. https://doi.org/10.1007/s11069-012-0528-3

Rahman, A.U., Shaw, R., 2015. DRR at the Local Government Level in Pakistan. pp. 259–279. https://doi.org/10.1007/978-4-431-55369-4_14

Rahman, Z.U., Ullah, W., Bai, S., Ullah, S., Jan, M.A., Khan, M., Tayyab, M., 2023. GIS-based flood susceptibility mapping using bivariate statistical model in Swat River Basin, Eastern Hindukush region, Pakistan. Front Environ Sci 11. https://doi.org/10.3389/fenvs.2023.1178540

Rana, I.A., Asim, M., Aslam, A.B., Jamshed, A., 2021. Disaster management cycle and its application for flood risk reduction in urban areas of Pakistan. Urban Clim 38, 100893. https://doi.org/10.1016/j.uclim.2021.100893

Rana, I.A., Routray, J.K., 2018a. Integrated methodology for flood risk assessment and application in urban communities of Pakistan. Natural Hazards 91, 239–266. https://doi.org/10.1007/s11069-017-3124-8

Rana, I.A., Routray, J.K., 2018b. Multidimensional Model for Vulnerability Assessment of Urban Flooding: An Empirical Study in Pakistan. International Journal of Disaster Risk Science 9, 359–375. https://doi.org/10.1007/s13753-018-0179-4

Rebi, A., Hussain, A., Hussain, I., Cao, J., Ullah, W., Abbas, H., Ullah, S., Zhou, J., 2023. Spatiotemporal Precipitation Trends and Associated Large-Scale Teleconnections in Northern Pakistan. Atmosphere (Basel) 14, 871. https://doi.org/10.3390/atmos14050871

Salman, A., Hassan, S.S., Khan, G.D., Goheer, M.A., Khan, A.A., Sheraz, K., 2021. HEC-RAS and GIS-based flood plain mapping: A case study of Narai Drain Peshawar. Acta Geophysica 69, 1383–1393. https://doi.org/10.1007/s11600-021-00615-4

Sarhadi, A., Soltani, S., Modarres, R., 2012. Probabilistic flood inundation mapping of ungauged rivers: Linking GIS techniques and frequency analysis. J Hydrol (Amst) 458–459, 68–86. https://doi.org/10.1016/j.jhydrol.2012.06.039

Scionti, F., Miguez, M.G., Barbaro, G., De Sousa, M.M., Foti, G., Canale, C., 2018. Integrated Methodology for Urban Flood Risk Mitigation in Cittanova, Italy. J Water Resour Plan Manag 144. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000985

Serre, D., Heinzlef, C., 2018. Assessing and mapping urban resilience to floods with respect to cascading effects through critical infrastructure networks. International Journal of Disaster Risk Reduction 30, 235–243. https://doi.org/10.1016/j.ijdrr.2018.02.018

Shah, I., Elahi, N., Alam, A., Dawar, S., Dogar, A.A., 2020. Institutional arrangement for disaster risk management: Evidence from Pakistan. International Journal of Disaster Risk Reduction 51, 101784. https://doi.org/10.1016/j.ijdrr.2020.101784

Sowmya, K., John, C.M., Shrivasthava, N.K., 2015. Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. Natural Hazards 75, 1271–1286. https://doi.org/10.1007/s11069-014-1372-4

Tayyab, M., Zhang, J., Hussain, M., Ullah, S., Liu, X., Khan, S.N., Baig, M.A., Hassan, W., Al-Shaibah, B., 2021. GIS-Based Urban Flood Resilience Assessment Using Urban Flood Resilience Model: A Case Study of Peshawar City, Khyber Pakhtunkhwa, Pakistan. Remote Sens (Basel) 13, 1864. https://doi.org/10.3390/rs13101864

Ullah, S., You, Q., Ullah, W., Ali, A., 2018. Observed changes in precipitation in China-Pakistan economic corridor during 1980–2016. Atmos Res 210, 1–14. https://doi.org/10.1016/j.atmosres.2018.04.007

Ullah, W., Wang, G., Lou, D., Ullah, Safi, Bhatti, A.S., Ullah, Sami, Karim, A., Hagan, D.F.T., Ali, G., 2021. Large-scale atmospheric circulation patterns associated with extreme monsoon precipitation in Pakistan during 1981–2018. Atmos Res 253, 105489. https://doi.org/10.1016/j.atmosres.2021.105489

United Nations Development Programme, 2010. UNDP Responds to Pakistan Floods, Plans for Recovery - Pakistan | ReliefWeb [WWW Document]. News and Press Release. URL https://reliefweb.int/report/pakistan/undp-responds-pakistan-floods-plans-recovery (accessed 8.22.20).

Waseem, H. Bin, Rana, I.A., 2023. Floods in Pakistan: A state-of-the-art review. Natural Hazards Research. https://doi.org/10.1016/j.nhres.2023.06.005

Zhang, X.Q., 2016. The trends, promises and challenges of urbanisation in the world. Habitat Int 54, 241–252. https://doi.org/10.1016/j.habitatint.2015.11.018

New References

Government of Pakistan [GOP]. (2017, November 10). Pakistan Tehsil Wise Census 2017. Retrieved from Pakistan Bureau of Statistics: http://www.pbscensus.gov.pk/sites/default/files/PAKISTAN%20TEHSIL%20WISE%20FOR%20WEB%20CENSUS_2017.pdf

Government of Pakistan [GOP]. (2018, January 03). Pakistan Bureau of Statistics (PBS) . Retrieved from Block Wise Provisional Summary Results of 6th Population & Housing Census - 2017: http://www.pbscensus.gov.pk/sites/default/files/bwpsr/kp/SWABI_BLOCKWISE.pdf

Government of Pakistan [GOP]. (1999). *District Census Report of Peshawar.* Islamabad, Pakistan: Statistic Division Population Census Organization, Printing Press, Islamabad, Pakistan.

Abbas, S., Yaseen, M., Latif, Y., Waseem, M., Muhammad, S., Kebede Leta, M., . . . Khan, T. H. (2022). Spatiotemporal analysis of climatic extremes over the Upper Indus Basin, Pakistan. *Water, 14*(11), 1718.

Amani, M., Ghorbanian, A., Ahmadi, S. A., Kakooei, M., Moghimi, A., Mirmazloumi, S. M., . . . Parsian, S. (2020). Google earth engine cloud computing platform for remote sensing big data applications: A comprehensive review. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 13*, 5326-5350.

Armaş, I., & Gavriş, A. (2013). Social vulnerability assessment using spatial multi-criteria analysis (SEVI model) and the Social Vulnerability Index (SoVI model)–a case study for Bucharest, Romania. *Natural Hazards and Earth System Sciences, 13*(6), 1481-1499.

Crop, I. (2015). IBM SPSS statistics for windows, Version 23.0. *Armonk, Ny, IBM Crop*.

Desktop, E. A. (2011). Release 10. *Redlands, CA: Environmental Systems Research Institute, 437*, 438.

Fuchs, S., Birkmann, J., & Glade, T. (2012). Vulnerability assessment in natural hazard and risk analysis: current approaches and future challenges. *Natural Hazards, 64*, 1969-1975.

Holand, I. S., Lujala, P., & Rød, J. K. (2011). Social vulnerability assessment for Norway: A quantitative approach. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography, 65*(1), 1-17.

Hussain, A., Cao, J., Ali, S., Ullah, W., Muhammad, S., Hussain, I., . . . Abbas, H. (2022). Variability in runoff and responses to land and oceanic parameters in the source region of the Indus River. *Ecological Indicators, 140*, 109014.

Hussain, A., Hussain, I., Ali, S., Ullah, W., Khan, F., Rezaei, A., . . . Cao, J. (2023). Assessment of precipitation extremes and their association with NDVI, monsoon and oceanic indices over Pakistan. *Atmospheric Research*, 106873.

Kappes, M. S., Papathoma-Koehle, M., & Keiler, M. (2012). Assessing physical vulnerability for multi-hazards using an indicator-based methodology. *Applied Geography, 32*(2), 577-590.

Kumar, S., Kumar, R. S., & PRABHU, M. G. N. (2020). Sampling framework for personal interviews in qualitative research. *PalArch's Journal of Archaeology of Egypt/Egyptology, 17*(7), 7102-7114.

Moret, W. (2014). Vulnerability assessment methodologies: A review of the literature. *Washington, DC: FHI, 360*.

Nawaz, F., Wang, T., & Hussain, A. (2023). Spatiotemporal Runoff Analysis and Associated Influencing Factors in Chitral Basin, Pakistan. *Water, 15*(12), 2175.

Singh, A., Kanungo, D., & Pal, S. (2019). Physical vulnerability assessment of buildings exposed to landslides in India. *Natural Hazards, 96*, 753-790.

Taherdoost, H. (2016). Sampling methods in research methodology; how to choose a sampling technique for research. *How to choose a sampling technique for research (April 10, 2016)*.

Taherdoost, H. (2017). Determining sample size; how to calculate survey sample size. *International Journal of Economics and Management Systems, 2*.

Wiles, R., Crow, G., Heath, S., & Charles, V. (2008). The management of confidentiality and anonymity in social research. *International journal of social research methodology, 11*(5), 417-428.