SOCIAL SCIENCE REVIEW ARCHIVES ISSN Print: 3006-4694
ISSN Online: 3006-4708
https://policyjournalofms.com

Geospatial Mapping and Assessment of Urban Flood Risk and Vulnerability in Rawalpindi, Pakistan

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DOI: https://doi.org/10.70670/sra.v3i4.1248

Abstract
Frequent and severe urban flooding in Rawalpindi, Pakistan, poses significant risks to both human populations and critical infrastructure, with vulnerability aggravated by rapid urbanization, inadequate drainage, and the compounding effects of climate change. This study assesses the flood vulnerability of Rawalpindi's urban zones, Rawalpindi Metropolitan, Rawalpindi Cantonment, and Chacklala Cantonment using a Flood Vulnerability Index (FVI), which integrates social, economic, physical (infrastructure), and environmental indicators. Primary and secondary data were collected through household surveys (386 responses from 32 identified vulnerable areas), and focus group discussions with relevant authorities while secondary data were explored from institutional records (WASA, RDA, PMD, Rescue 1122). The stratified probability sampling method ensured representative coverage of at-risk communities, while field surveys captured on-ground realities of exposure, susceptibility, and resilience. The collected data were analyzed with the help of SPSS and applied statistical methods like correlation and regression etc. Vulnerable areas were demarcated using GIS mapping, and the FVI was calculated. The data was normalized, assigned specific weightage to each indicator and impact value of each indicator was calculated. The results indicate moderate to high flood vulnerability across the study area, with the Rawalpindi Metropolitan (RM) exhibiting the highest FVI (0.5), primarily due to social and physical weaknesses. Economic vulnerability was notably high in Rawalpindi Cantonment (0.61), whereas Chacklala Cantonment showed comparatively lower overall vulnerability (0.363). The study reveals widespread social vulnerability and highlights the cyclical impact of flooding on low-income communities. The study concludes that targeted mitigation strategies including improved urban planning, enhanced drainage infrastructure, community-based early warning systems, and policies to direct growth away from floodplains are urgently needed to reduce vulnerability. The FVI framework offers a practical tool for policymakers to prioritize interventions in the most at-risk areas, supporting sustainable urban development and disaster risk reduction in rapidly growing cities like Rawalpindi.

Keywords: Flood, Rawalpindi, Exposure, Susceptibility, Resilience

Introduction
Flood is a phenomenon where the water over flows streams and submerge surrounding areas otherwise away from flowing water. (Waseem & Rana, 2023).` Most common factors of flood are distance from river, rainfall slop and altitude (Morales-Ruano et al., 2022; Ahmad et al., 2025). Heavy

rainfall especially during monsoon is major cause of surface runoff, overflow of drainage capacity and flooding (Hashmi et al., 2012). Flood causes heavy damages in rural and urban areas. Poor drain quality (Douben, 2006) and rapid urbanization and local climatic changes are foremost factors to trigger the urban flooding (Zeleňáková et al., 2017).

When we focus on major causes of urban flooding, we observe natural and anthropogenic factors both. Natural gradient, soil type, amount of rainfall, presence of nullah or streams are common factors, while anthropogenic factors include ignorance of Public by laws, rapid and unplanned urban growth. Unplanned urban sprawl, encroachment, shanty town usually block the natural flow of drainage. Low lying flood plan (flat area) generally attract for settlement due to easy landscaping, vast transport network and fertile agriculture land (Nott, 2006; Ahmad et al. 2020). Low lying area become densely populated with irregular settlement. It ultimately turns pervious surface into impervious surface. This type of surface reduces water absorption and trigger surface runoff. In case of rainfall, rapid and heavy runoff damages buildings, wash away infrastructure and cause health hazards (Aladelokun & Ajayi, 2014).

Flood causes damages to infrastructure, cost of lives and widespread damage to economy and natural environment. (Rahman, 2014). In China, study found that due to urbanization (extension of built-up area and change LULC types) an increase (208 to 413%) in surface runoff is induced. Increased impervious surface directly impact on surface runoff and overburdened drainage system (Zhou et al., 2019). Study of Salzburg Austria revealed concentration of historic building as one of the chief social issue behind urban flooding (Kienberger et al., 2014). Flood risks and damages could be reduced with urban growth management also directing expansions and populations away from floodplains (Su1 et al., 2016). Climate change and urbanization are reasons of variations in urban extreme rainfall events. Growing cities, due to perturbation of Urban Heat Island UHI, either increase rainfall or overturn due to low humidity and increasing aerosol load. That is why there is variation in precipitation pattern form city to city (Zhou et al., 2017).

Pakistan, like many other South Asian developing countries is facing rapid urbanization (Vasenev et al., 2019). The phenomena of urbanization is increasing in the degree and scale in Pakistan (Shah et al., 2022) is credited to the natural population growing (Kugelman, 2014) and migration from rural-to-urban areas (Salik et al., 2017).This huge migration is because of the odd historic (Farah et al., 2012; Farooq et al., 2005; Safder & Babar, 2019), economic (Chiesura & De Groot, 2003; De Molina & Toledo, 2014; Gilani et al., 2020), social (Lopes & Farooq, 2020), geo-strategic and environmental (Shaheen et al., 2020) dynamics of Pakistan.

Urban flooding is a phenomenon which occurs after heavy rainfall overwhelmed by drainage capability. Urban flood is potential threat to men and infrastructure**.** In Pakistan, Urban areas in general and mega cities in particular facing great threat of urban flood especially during monsoon seasons. According to World Bank Report, mega cities like Karachi, Lahore, Faisalabad, Multan and Rawalpindi, during last decade, have faced worst incidents of urban flooding. There are number of factors which trigger the dilemma of urban flooding, those include climatic change in local conditions, but topmost is urbanization. The urbanization reduces impervious and spongy surface with the expansion of paved road and cemented buildings etc. (Zia et al., 2021). In addition to the other reasons, streams flowing through urban areas are one of the major sources of urban flooding. The streams like Gujar Nullah, Orangi Nullah, Manzoor colony Nullah of Karachi and Lai Nullah of Rawalpindi overflow and cause heavy damage to low lying adjacent areas. Rawalpindi a mega city, especially areas of old city are highly vulnerable to urban flooding due to heavy monsoon rainfall vis-à-vis overflow of Nullah Lai and poor drainage system. The study will identify the flood vulnerable areas and calculate Flood vulnerability Index (FVI) of those areas. The study area is administratively divided into three major sub-regions known as Rawalpindi Metropolitan (RM), Rawalpindi Cantonment (RC) and Chacklala Cantonment (CC). FVI of all three sub-regions collectively and individually will be calculated and compare to ascertain the scale of Vulnerability and requirement of mitigation measures. The study will further calculate sub categories or components of FVI including, Social, Physical, Environment and Economic Flood Vulnerability Index of whole study area and individual sub-region.

The physical system is changing, which increases susceptibility, risk, and exposure to flood threats. Other characteristics that promote vulnerability to flood hazards include landlessness, ethnic cultural practices, low residential and professional mobility, and persistent poverty. (Chan, 2015). Studies found that socio-economic characteristics of community are closely associated with perception of flood risk. The characteristics includes education, age, house ownership, size of family, distance from source/river or stream, access to credit even information about forecasts (Shah et al., 2022).Therefore, at community level, major indicators of causes and level of damages are socio-economic factors which further termed as recently evolved term vulnerabilities (Balica et al., 2009).

An integral component of sustainability science and disaster risk reduction is vulnerability assessment. (Turner et al., 2003; Zhou et al., 2015). Vulnerability is measured through five dimensional indicators; social, economic , physical (infrastructure), institutional, attitudinal(Rana & Routray, 2018). In order to analyze vulnerability, one should consider the individual or community, which is made up of five elements: governance, self-defense, social protection, livelihood, and people's status (Cannon, 2008). Several criteria for making decisions like Hierarchy Analysis Process (AHP) and Multicriteria Decision Analysis MDA methodology work well together to identify locations that are vulnerable to flooding (Morales-Ruano et al., 2022). Vulnerability of an urban area is measured using socio-economic variables coupled with physical components including hydrological and hydraulic model. The results of an area’s Flood Vulnerability Index (FVI) make it easier for decision makers to plan for the future and choose which regions should receive intervention based on stakeholder preferences or the most susceptible areas (Salazar-Briones et al., 2020). Increasing impervious surface changes, the hydrological cycle and creates the conditions where the surface does not support diversification of life. Thus, impervious surface directly proportion to flood vulnerability of urban area (Saraswat et al., 2016). FVI methodology is a systematic way to measure flood vulnerability. Multiple regression analysis, analyses the relationship between flood vulnerability/risk economic vulnerability (Hashim, 2019).

FVI is calculated by classifying the indicators to the features which belong to susceptibility, exposure and resilience. FVI Factors, Components and Indicators. The particular indicators of exposure and susceptibility are multiplied and then divided by the resilience indicators. Since, indicators representing exposure and susceptibility increases the flood vulnerability hence placed in the nominator. The ‘R’ resilience indicators decrease flood vulnerability and are thus part of the de-nominator (Cendrero, 1997). Therefore, in this study Flood Vulnerability Index will be used as model to measure the exposure to the flood for recommendation of mitigation measures.

Exposure of objects like persons, infrastructure, goods, men and material even ecological eco-system etc. may be affected during and after urban flood (Solecki et al., 2011). Vulnerability can also be associated with its function and act at household or community level (Cutter, 1996). Vulnerability can be accessed in term of danger to economic entities by flood. It may be at household, community, regional level or overall infrastructure (Balica et al., 2009; Logtmeijer, 2005).

Susceptibility to disaster also has direct link with poverty. Low income level forced people to dwell in poor socio-economic conditions. Due to limited financial resources, people are compelled to live in flood plain, slums & hazardous areas. Due to poor infrastructure and limited resources viz-a-viz lack of assistance by govt agencies, such communities do not get early warnings. Even if they are warned, they do not have sufficient resources and management skill or capacity of resilience or coping with flood or any other hazard (Rahman, 2014). In low income communities, poor household do not have or very limited resources of rehabilitation (Blaikie et al., 2014). It is further observed that weakness is cyclical. If damage to household cause in one season then the infrastructure will be more vulnerable in next rainy seasons on flood hazard. Social, political, institutional, and cultural factors can all contribute to vulnerability.

Resilience is the capability to check or moderate damages and then, in the face of damage to return to normal life as far as possible and to manage rescue from the effects (Buckle et al., 2000). The degree to which metropolises can withstand some upheaval before reconfiguring on the basis of new structures and techniques is known as urban resilience (de Bruijn, 2004). The ability of an urban system as well as all of its socio-technical and socio-ecological grid components to maintain or quickly regain a desired goal in the event of a disorder, to adapt to change, and to quickly update the entire system that halts present or future adaptive capability is another definition of urban resilience. (Meerow et al., 2016). Urban resilience includes the thinking that urban area should regain their normal life from untoward situation as early as possible (Proverbs & Lamond, 2009). Resilience can be broken into four fundamental characteristics, or the '4Rs': redundancy, robustness, rapidity, and resourcefulness (Atreya & Kunreuther, 2021; Lee et al., 2021).

Urban flood resilience is the ability of a city to prepare for, withstand, and recover from flood events, minimizing their impact on people, the economy, and infrastructure. Unlike traditional flood management that focuses on keeping water out with large-scale 'grey' infrastructure like levees and floodwalls, resilience acknowledges that some level of flooding is inevitable due to climate change and rapid urbanization. Therefore, it emphasizes a holistic, multi-layered approach that combines structural measures with social, economic, and environmental strategies.

Material and Methods

The study is primarily based on primary and secondary data. The secondary data was acquired from [1]WASA, PMD, RESCUE 1122, RDA, RMC, RCB, CCB and Army Flood relief cell, whereas, household survey was carried out to collect primary data.

Primary Data Sources

In order to gather data, primary sources were investigated. Household surveys, the Army Flood Rescue Center, Rawalpindi Development Authority (RDA) RESCUE 1122, and Local Government Units, such as the Water and Sewerage Authority (WASA), were among these sources. To collect primary data, a structured questionnaire was employed.

Field Survey

Urban flooding is a serious threat to the socio-economic conditions and lives of the communities particularly those residing in vulnerable areas of rapidly expanding towns and cities of developing countries (Villordon & Gourbesville, 2016). An essential component of the study that assesses residents' strengths and weaknesses in the event of an urban flood is a household survey. For this task a structured questionnaire was designed to survey the selected areas, focusing on vulnerable areas. The survey helps to gauge the extent of damage to socio-economic fiber in case of flood. Also highlights potentially vulnerable areas. The data is also useful for assessing the system's resilience efficiency and mitigation strength in terms of its social, economic, environmental, and physical components. Field survey a primary requirement of the study is also a multistep process. It entails designing of questionnaire with carefully chosen indicators, selection of population and its size, target groups, sampling size and survey techniques, etc.

Designing of Questionnaire

For the study, the questionnaire was designed with qualitative-based questions. Most of the questions were closed-ended, and carefully categorized during the pre-analysis of the questionnaire.

Selection of Indicators

The study's primary objective is to assess the flood risk of particular regions to make additional recommendations for mitigation measures. Exposure, Susceptibility, and Resilience are the three primary factors used to generate the Flood Vulnerability Index. These factors have grouped indicators

[1] WASA: Water and Sanitary Authority, PMD: Pakistan Metrological Department, RDA: Rawalpindi Development Authority, RMC: Rawalpindi Metropolitan Corporation, RCB: Rawalpindi Cantonment Board, CCB: Chacklala Cantonment Board

(Zia et al., 2021). A Disaster Resilience Index comprising six key dimensions social, economic, institutional, community, environmental, and community capital was developed by Moghadas in 2019. These dimensions are further grouped into indicators (Moghadas et al., 2019). The current study, considering the typical socio-economic conditions of developing countries, has selected 34 indicators for Vulnerability and Disaster Resilience.

Population Selection and Sample Size

The target population was those living in various parts of Rawalpindi city and cantonment**.** The target areas were selected based on socio-economic conditions, spatial characteristics, and history of flooding. RESCUE 1122, the Pakistan Meteorological Department, the Rawalpindi Development Authority, and the Water and Sanitation Authority also designated the survey sites as susceptible areas. A total of 386 households from 32 designated vulnerable points were surveyed through a structured questionnaire. The Fig 1 highlights Rawalpindi's most vulnerable neighborhoods as determined by institutions.

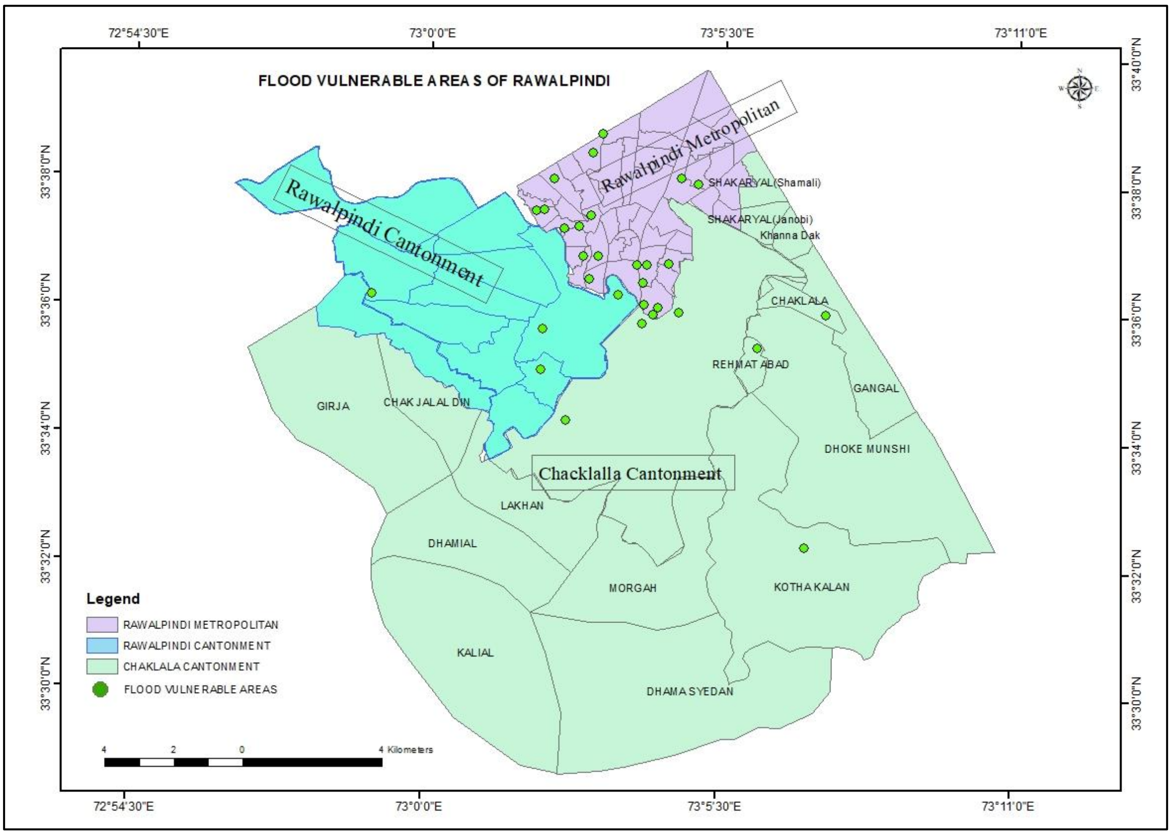

Fig 1: Map of study area indicating vulnerable points

Sampling Techniques

Stratified probability sampling techniques were used for the household survey. Every respondent is selected from random samples in several groups, making the technique appropriate for a huge population. Thirty two vulnerable areas were distributed into areas of Rawalpindi Metropolitan, Rawalpindi Cantt and Chacklala Cantt. Therefore, these 32 vulnerable areas of city and cantonments were taken as separate groups. Subsequently, a household survey of selected areas of Rawalpindi was carried out, and collected random data.

Survey method selection for data collection

There are multiple methods of data collection like conventional door-to-door surveys, telephonic surveys, or modern techniques of electronic survey through the internet. For the study, a pilot survey using two methods i.e. household and online survey through Google form was tested. Both methods have some pros and cons. The response to the Google form was neither confirmed nor authentic. Whereas, the household survey was sure to get requisite data with the personal effort of the surveyor. However, this method was costly and time-consuming. Another issue with the electronic survey was that the target population was not aware of the importance of the survey, and also deprived of the requisite technology. Face-to-face household survey is most appropriate for urban flood studies (Shah et al., 2017). Therefore, it was decided to undertake a door-to-door house survey for the study.

Exclusive meetings with authorities of WASA, RDA, PMD, and RESCUE 1122 were conducted. A pilot survey of the general study area was also conducted. These measures have helped to earmark trouble or vulnerable areas. Those areas were focused on for the final survey. In the light of pilot survey and guidelines of the institutions, certain changes were made to finalize the questionnaire. Keeping in view the literacy level of the target population, an Urdu version of the questionnaire was also launched. Respondents (mostly women) who were reluctant to answer during the briefing phase were swapped out for another family during the survey (Bogner et al., 2009).

Focus Groups Discussion

Authorities of concerned institutions were approached for relevant information. The researcher has visited various departments. Director Nullah Lai section of PMD was interviewed and got valuable information including vulnerable areas maps and their early flood warning system. Deputy Director WASA was contacted and got important information on pre-flood preparation like the dredging schedule of Nulla Lai and maintenance of drainage system. RESCUE 1122 and the Army Flood control cell have provided valuable information like rescue missions during and after floods and sites for the establishment of rescue shelters etc. The meetings helped to estimate the intuitional resilience of Rawalpindi and their shortcomings.

Secondary Data Sources

The following sources were approached for the provision of secondary data.

Water and Sanitation Authority (WASA) Rawalpindi

It is a government organization that plans, designs, develops, and maintains Pakistani cities' drainage, sewage, and water supply systems. In addition to measuring the depth of flood water, the organization keeps track of information on the locations of sore spots, the drainage system's present capacity, and regions that might be swamped in the event of rains. The WASA is responsible for widening the Nullah Lai before monsoon to maintain its flow within the limit to avoid a flood. WASA is recording urban flood events with the help of citizen's complaints. During the last few years' urban flood events have been quantifying basing on complaints received in call centers. Despite being a useful source of information on urban flood disasters, citizen call data is unstructured and raw, which means it takes a lot of work to prepare the data for use in quantitative analysis (Spekkers et al., 2011; Ten Veldhuis et al., 2013). Another source of data with WASA was explored for the drainage network. There were three drainage classes identified known as primary, secondary, and tertiary pipeline. These pipelines were further classified as per the diameter. The pipelines accommodate the flow of water according to their diameters.

Pakistan Meteorological Department (PMD)

Rain gauge stations are the only sources to provide accurate rainfall data (Earls & Dixon, 2007). Monthly rainfall data from 1980 to 2023 was taken from PMD, but it was only of one rain gauge station called Zero-point Islamabad. The 2001 urban flood of Rawalpindi was a whistle-blowing event. During the post-2001 flood period, more rain gauge stations were set up. Currently, there are six rain gauge stations in Islamabad and Rawalpindi. Rainfall data from 2007 onwards is available on daily basis and more structured. For general analysis, data from 1980 to 2023 was referred to, however, rainfall data from 2007 to 2023 acquired from six rain gauge stations was analyzed for an in-depth study of floods. An exclusive Nullah Lai wing has also been established in PMD. The wing maintains the telemetry system of Nullah Lai and is responsible for issuing flood warnings. The data regarding the cross-section of Nullah Lai along with the water level has also been provided by PMD

(PMD, 2024a). Detail of rainfall of corresponding rain gauge stations is given in tables in succeeding paragraphs.

Data Analysis

The data was examined in light of the study's objectives. Initially, spatial, and temporal analyses have been done to identify the sore points by the development of geodatabase. Using a household survey, the second phase involved analyzing hotspot locations that had been spatially located to determine the primary socio-economic and environmental causes. The data was further analyzed using Statistical Package for Social Scientist- 7(SPSS) and MS Excel.

Profile of Study Area

Rawalpindi city is core study area as highlighted in fig 2. Rawalpindi city is located at Latitude 33º 36′ 52″ N, Longitude 73º.04′ 44″ E. Rawalpindi city with area of 143 sq. km is ranking 4th among large cities of Pakistan and located in foothills of Magella hills, north western part of Pakistan. Another significance of the city is its role as one of the twin cities (Rawalpindi-Islamabad), 4th largest Metropolitan of Pakistan.

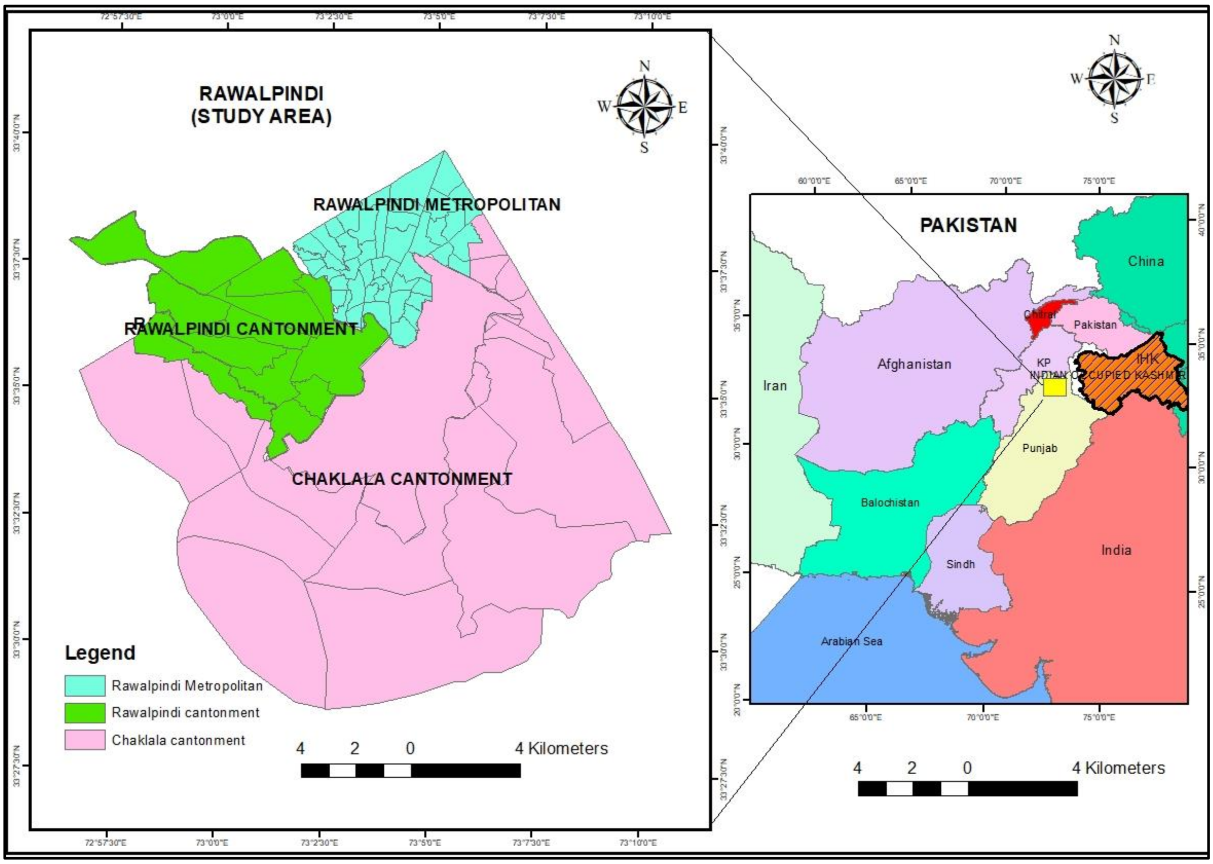

Figure 2: Location Map of Rawalpindi, Pakistan

The city has well connected road rails, network and one of the largest Airport. Being economic hub, Rawalpindi has rich textile, food processing and light manufacturing industries. According to 2023 census, the city is 4th and 3rd most populous city in Pakistan and Punjab respectively. The city with high density of population is overcrowded, congested, and has extensive build up areas. Especially inner city or old city of Rawalpindi. Institutions like Rawalpindi Development Authority, Water and sanitation Authority (WASA), Rawalpindi Cantonment Board (RCB) are responsible for sustainable development of the city. They endeavor to meet the challenges of urban sprawl, slum development and other environmental issues. Among other, urban flooding is a major challenge, especially inner/old part of the city. Side by side factors like poor sewerage system, unplanned settlement, congestion, heavy rainfall, Nullah lai, a major stream is prominent cause of urban flooding in Rawalpindi city. The city lies in the basin of Nullah lai. The basin of Nullah lai and its tributaries is divided into upper and lower part mainly consists of Islamabad & Rawalpindi respectively. Administratively, Rawalpindi is divided into Rawalpindi Metropolitan, Rawalpindi Cantonment and Chacklala Cantonment being administered by [2]RMC, RCB and CCB. The basin of Nullah Lai is located between 33º33′ & 33º46′N &72º55′& 73º07′E. Thus, covers total 234.8km^2 catchment area. The basin has 161.3km^2(69%) upper portion, mainly Islamabad capital city and 73.6km^2 lower part consist of Urban areas of Rawalpindi. (JICA, 2003). The basin faces major challenges of urban flooding, especially during monsoon season. Overflow of Lai & tributaries causes heavy damages to men and material.

According to Köppen climate classification, Rawalpindi city is humid Sub-tropical (Kamran et al., 2023). The climate can be classified as 'Sub Tropical Triple Season Moderate Climate Zone' having monsoon rainfall July-September. The study area has hot summers upto 40^{o}C in Jun/July and cold winter lower to 0^{o}C in December. As far as rainfall is concern, out of 1000 mm annual rainfall, 60% occurs during main-rainy season or monsoon season.

Results

Development of Urban areas' flood vulnerability index

The vulnerability of an area is accumulation of factors which expose the area , create susceptibility and reflects its resilience strength (Balica et al., 2012). The area's exposed elements that indicate the likelihood of being injured by a flood are known as susceptibility (Nasiri & Shahmohammadi-Kalalagh, 2013). Whereas , resilience is capacity of a community with which it adopts changes in hazardous area with modifications (Galderisi et al., 2005).

According to Huang et al. (2012), there are four components to multidimensional vulnerability: population vulnerability, mortality vulnerability, agriculture, and economic vulnerability. In the context of urban regions, however, the FVI method as described is more applicable.(Balica et al., 2012) The general formula for FVI is determined by classifying the components into three indicator groups: resilience (R), susceptibility (S), and exposure (E).

$$FVI = \frac{Exposure * Susceptibility}{Resilience} * 10 \text{\_\_\_\_\_\_\_\_ Eq (1)}$$

With regards to urban flood indicators, the equation converts into following. The acronyms are explained in Table 3. Whereas detail calculation of factors are given in Table 5 to 8 of appendix II.

$$FVI\ (social) = \frac{HH*Finfo*GRP*PRP*NRP*CRP*SMM*Snow}{Edn*Hsize*Htenrre*FIS*ADLF*Ctrg} * 10 \text{ \_\_\_\_\_ Eq (2)}$$

$$FVI\ (Econimc) = \frac{Hage*FR*MH*FDH}{CRpre-f*CRpost-f} * 10 \text{ \_\_\_\_\_\_\_\_\_\_ Eq (3)}$$

$$FVI\ (Environment) = \frac{LFE*FWL*FWD*LULC*Rain}{SWM*DFS} * 10 \text{\_\_\_\_\_\_Eq (4)}$$

$$FVI\ (Physical) = \frac{Elev*FMM*Hage*FR}{MTLF} * 10 \text{\_\_\_\_\_\_\_\_\_\_ Eq (5)}$$

[2] RMC: Rawalpindi Metropolitan Corporation, RCB: Rawalpindi Cantonment Board, CCB: Chcklala Cantonment Board

$$FVI = \frac{VI(social) + FVI\ (Economic) + FVI\ (Environment) + FVI\ (\ Physcial)}{4} \qquad Eq\ 6$$

Total FVI of each city area is average of these four FVI. The index value is as follow (Table 1):-

Table 1: FVI - Index values and their description

Index value	Description
<0.01	Very small vulnerability to flood
0.01-0.25	Small vulnerability to floods
0.25-0.5	Vulnerability to floods
0.5 – 0.75	High vulnerability to flood
0.75 – 1	Very high vulnerability to flood

Source: Adopted (Balica et al., 2012), 2024

The index shows an urban area's low or high flood risk as a value between 0 and 1. The method provides a direction to evaluate FVI of an area for future planning and mitigation measure. In present study the indicators were modified to adjust them according to the socio-economic and environmental condition of urban area of developing countries like Pakistan.

Computation of FVI of Study Area

A field survey was carried out and data of 386 households was taken. The relevant factors and indicators were grouped into Exposure, Susceptibility and Resilience. The study area is consisting of Rawalpindi Metropolitan, Rawalpindi cantonment and Chacklala cantonment. Overall FVI of study area and of three sub-regions are given in succeeding paragraphs.

Methodology for Household Survey Data Processing and FVI Calculation is as per following steps:

- **Step I**: Responses to 34 indicators collected through the household survey were analyzed, and frequency distributions were computed using SPSS software.
- **Step II:** The average frequencies of the household indicators were calculated using Microsoft Excel. Subsequently, these averages were normalized employing the following formula:

$$X(normalize) = \frac{X - X(\min)}{X(max) - X(min)}$$

Where; *X=Average value of factor, X(min) = minimum value, X(max) = maximum value*

- **Step III**: Weightages ranging from 1 to 10 were assigned to each household survey indicator based on their relative importance.
- **Step IV**: The normalized values of the indicators were multiplied by their respective weightages to determine the weighted impact of each variable. These impact values were then incorporated into the formula used to calculate the Flood Vulnerability Index (FVI). Detailed impact values are provided in Table 5 to 8 of Appendix II.

Cumulative FVI of study area and sub-regions: The Normalized values, weightages and final impact value of indicators of whole study area, sub regions, Rawalpindi Metropolitan, Rawalpindi Cantonment and Chacklala cantonment were calculated. Cumulative FVI of any place is the average of Social, Economic, Environment and Physical FVIs as indicated in equation as follow: -

$$FVI = \frac{FVI(social) + FVI\ (Economic) + FVI\ (Environment) + FVI\ (\ Physcial)}{4}$$

$$FVI\ of\ Rawalpindi\ study\ area = \frac{0.62 + 0.374 + 0.432 + 0.256}{4} = 0.42$$

$$FVI\ of\ RM^{3} = \frac{0.674 + 0.326 + 0.435 + 0.566}{4} = 0.5$$

$$FVI\ of\ RC = \frac{0.491 + 0.61 + 0.333 + 0.196}{4} = 0.4$$

$$FVI\ of\ \mathrm{CC} = \frac{0.592 + 0.443 + 0.162 + 0.257}{4} = 0.363$$

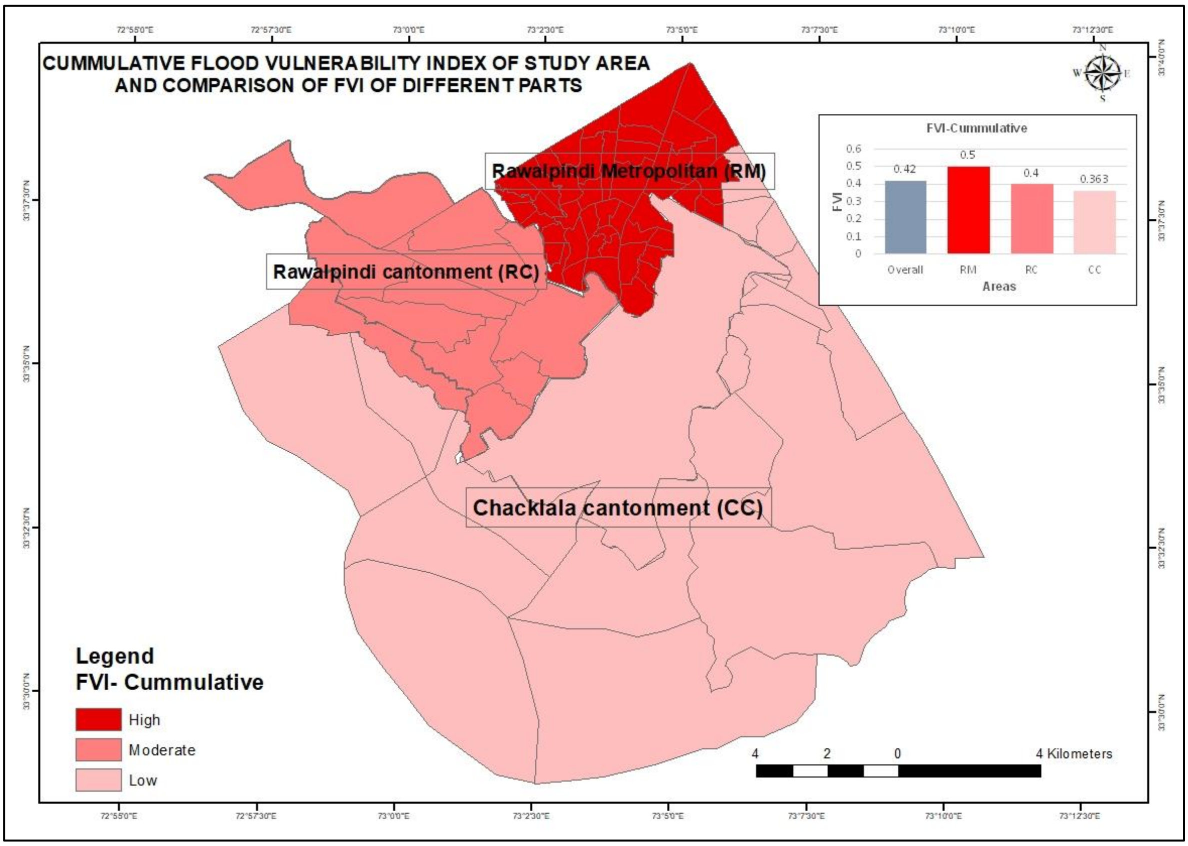

Fig 3: Map showing FVI (Cumulative) of study area and sub-regions RM, RC, CC

Source: Field survey, prepared by author, 2024

The overall Flood Vulnerability Index (FVI) for the study area is calculated as 0.42, classifying the region as flood-vulnerable. The Rawalpindi Metropolitan (RM), representing the administrative and historic core of Rawalpindi city, exhibits a notable susceptibility to urban flooding, as reflected by its overall Flood Vulnerability Index (FVI) of 0.5. This value categorizes the area as flood-vulnerable and highlights the need for targeted risk mitigation strategies. Rawalpindi cantonment is considered old cantonment but still better infrastructure than Rawalpindi Metropolitan old city. The overall FVI value of 0.4 places Rawalpindi Cantonment in a moderate flood vulnerability category. An FVI

[3] RM: Rawalpindi Metropolitan, RC: Rawalpindi Cantonment, CC: Chcklala Cantonment

(Flood Vulnerability Index) of 0.363 for Chacklala Cantonment indicates a moderate level of flood vulnerability. This value reflects the combined influence of social, economic, environmental, and physical factors contributing to the area's susceptibility to flooding. Specifically, a value around 0.36 suggests that while the cantonment is not among the highest risk zones, it still faces significant challenges related to flood exposure and sensitivity (Fig 3).

Social FVI of study area and sub-regions RM, RC and CCl

The Social Flood Vulnerability Index (SFVI) is a crucial tool designed to move flood risk assessment beyond purely physical and economic damage, focusing instead on the human dimensions of disaster.

$$FVI\ (social - study\ area) = \frac{0.195*0.1*0.260*0.203*0.181*0.212*0.234*0.350}{0.271*0.121*0.231*0.130*0.247*0.214} * 10 = 0.62$$

$$FVI\ (social - RM) = \frac{0.203*0.1*0.246*0.208*0.168*0.228*0.35*0.238}{0.276*0.123*0.216*0.122*0.253*0.217} * 10 = 0.674$$

$$FVI\ (social - RC) = \frac{0.163*0.1*0.322*0.195*0.181*0.224*0.35*0.247}{0.263*0.115*0.315*0.133*0.245*0.235} * 10 = 0.491$$

$$FVI\ (social - CC) = \frac{0.213*0.1*0.248*0.199*0.221*0.194*0.35*0.236}{0.289*0.122*0.199*0.154*0.256*0.227} * 10 = 0.592$$

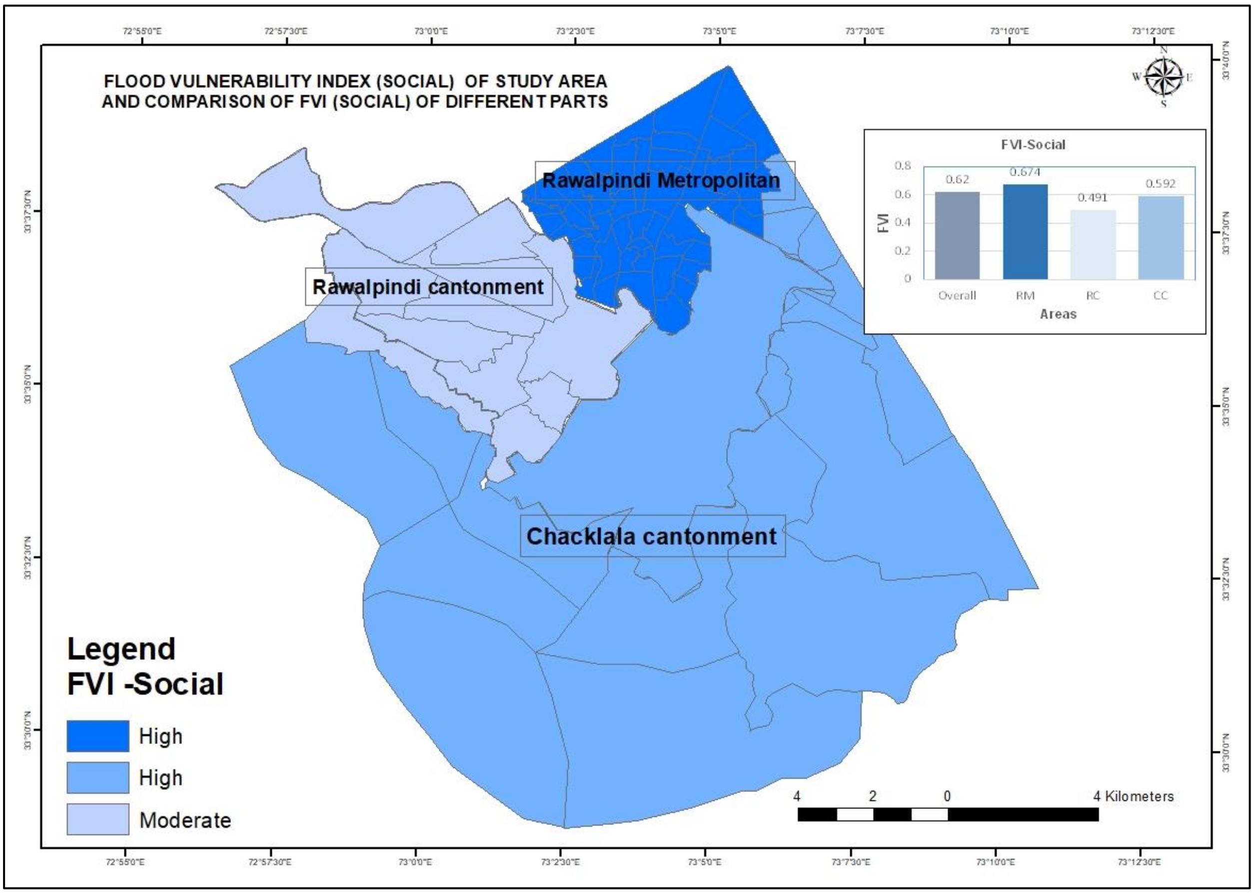

Fig 4: Map showing FVI (Social) of study area and sub-regions RM, RC and CC

A detailed examination of the FVI components of whole study area reveals that the social dimension exhibits a particularly high vulnerability, with an FVI (Social) value of 0.62, indicating significant susceptibility within the community's social structure. The social component of the FVI of Rawalpindi Metropolitan (RM) is particularly elevated, with a value of 0.674, indicating a high degree of social vulnerability to urban flooding. This heightened risk is primarily attributed to poor socio-economic conditions and a general lack of public awareness regarding flood preparedness and response. The social vulnerability component (0.592) of the Rawalpindi cant (RC) is the most significant contributor to flood risk, emphasizing the need for enhanced social resilience, community education, and awareness programs. The high Social Flood Vulnerability Index (SFVI) value of 0.592 for Chaklala Cantonment (CC) implies that the population in this area is highly susceptible to harm from flood events and has a significantly limited capacity to cope with, resist, and recover from their impact. This analysis underscores the urgent need for comprehensive flood risk management in RM, with particular emphasis on improving socio-economic conditions, enhancing public awareness, and strengthening physical infrastructure to reduce overall vulnerability (Fig 4).

Economic FVI of Study area and Sub-regions RM, RC and CC

The Economic Flood Vulnerability Index (EFVI) is an indispensable metric developed to systematically measure and map the potential financial and structural harm that floods can inflict upon a defined economic system, whether at the regional, municipal, or household level.

$$FVI\ (Economic - study\ area) = \frac{0.184 * 0.347 * 0.168 * 0.245}{0.281 * 0.252} * 10 = 0.375$$

$$FVI\ (Economic - RM) = \frac{0.167 * 0.189 * 0.347 * 0.218}{0..281 * 0.26} * 10 = 0.326$$

$$FVI\ (Economic - RC) = \frac{0.165 * 0.253 * 0.35 * 0.203}{0.237 * 0.205} * 10 = 0.61$$

$$FVI\ (Economic - CC) = \frac{0.169 * 0.285 * 0.34 * 0.181}{0.292 * 0.229} * 10 = 0.443$$

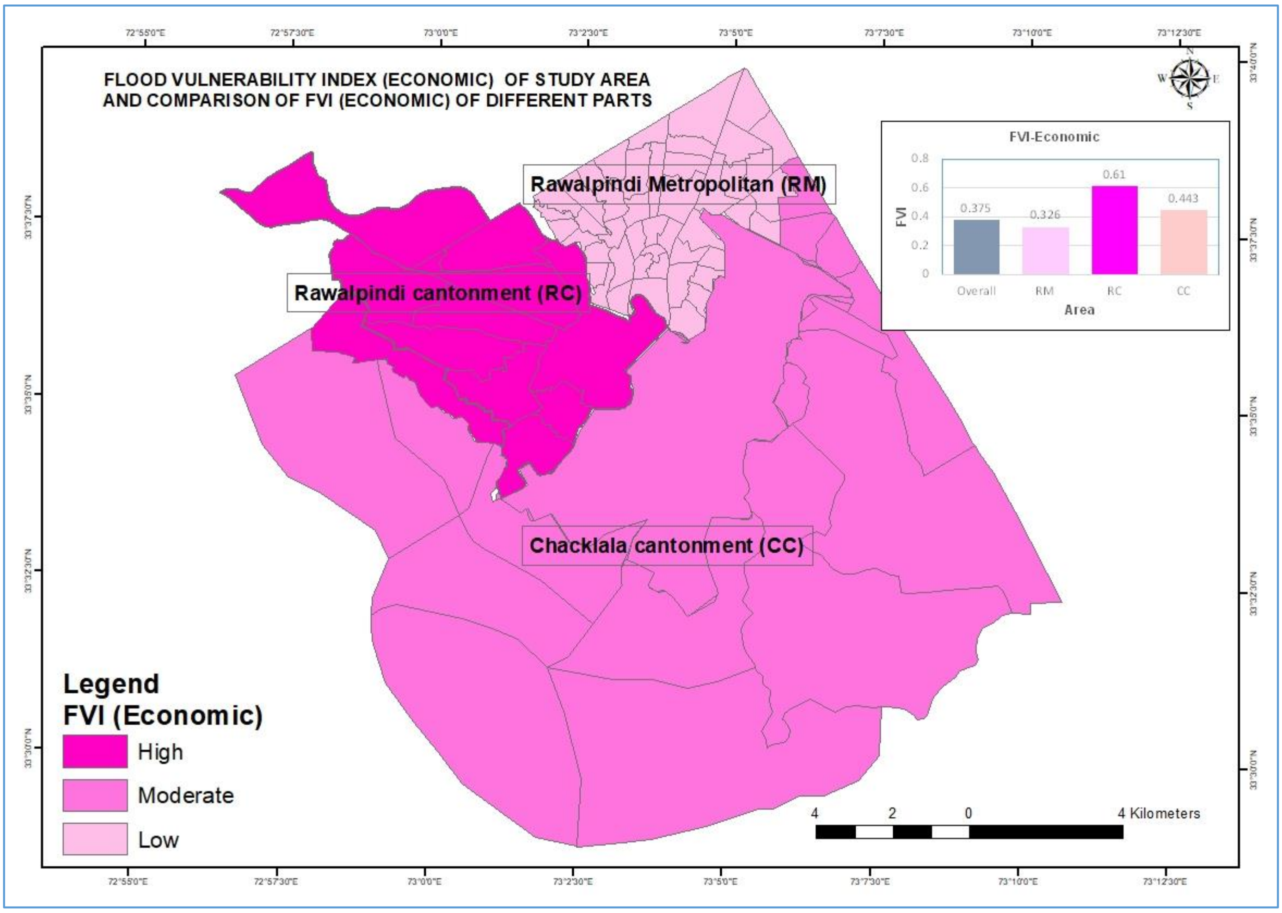

Fig 5: Map showing FVI (Economic) of Study area and sub-regions RM, RC and CC

Source: Field survey, prepared by author, 2024

The overall FVI (Economic) of study area is 0.375, posing moderate threat to economic infrastructure and activities. The economic component of RM stands at 0.326, though to a lesser extent than the social dimensions but still posing a threat to the economic infrastructure of the region. As far as components of FVI of RC is concern, economic component exhibits the highest vulnerability (0.61), indicating that economic factors such as income instability and livelihood risks are critical areas requiring intervention. The economic vulnerability (0.443) of CC also plays an important role, suggesting that economic stability and livelihood diversification should be addressed to reduce flood risk (Fig 5).

Environmental FVI of Study area and Sub-regions RM, RC and CC

The Environmental Flood Vulnerability Index (Env FVI) provides a critical lens for assessing how the natural condition and physical landscape of an area contribute to its overall susceptibility to flooding, as well as the capacity of the natural environment to mitigate or exacerbate flood impacts.

$$FVI\ (Environment - study\ area) = \frac{0.317 * 0.408 * 0.377 * 0.237 * 0.215}{0.35 * 0.164} * 10 = 0.432$$

$$FVI\ (Environment - RM) = \frac{0.309 * 0.36 * 0.41 * 0.237 * 0.215}{0.181 * 0.295} * 10 = 0.435$$

$$FVI\ (Environment - RC) = \frac{0.274 * 0.4 * 0.394 * 0.237 * 0.215}{0.267 * 0.427} * 10 = 0.333$$

$$FVI\ (Environment - CC) = \frac{0.405 * 0.332 * 0.34 * 0.237 * 0.215}{0.273 * 0.526} * 10 = 0.162$$

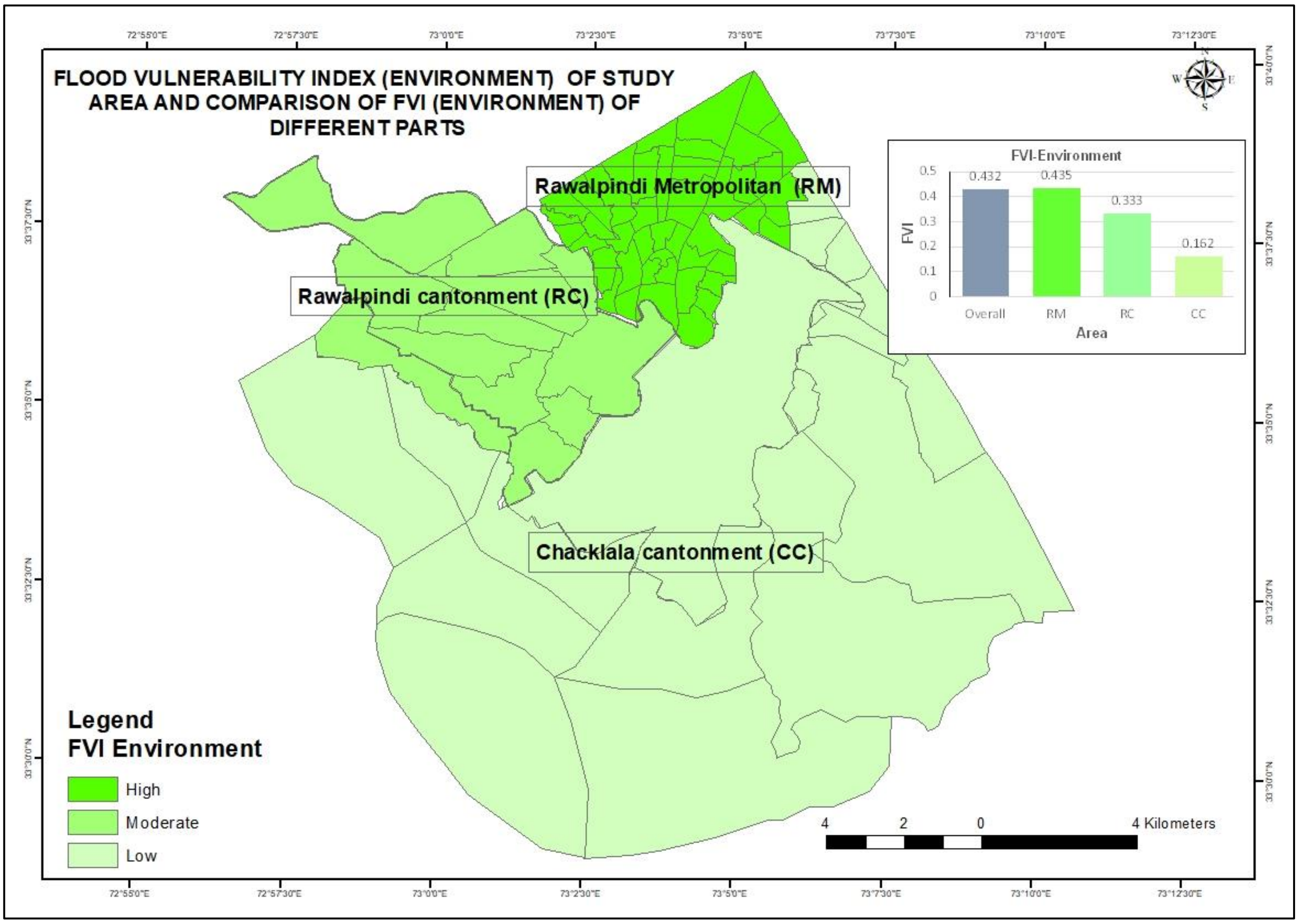

Fig 6: Map showing FVI (Environment) of Study area and sub-regions RM, RC and CC

Source: Field survey, prepared by author, 2024

The environmental component of study area with an FVI (Environment) of 0.422, also falls within the flood-vulnerable range, largely attributed to ongoing environmental degradation. The environmental component of RM records an FVI of 0.435, again posing a moderate threat of flood due to environmental degradation. Environmental vulnerability (0.333) of RC points to the importance of sustainable land use and environmental management to mitigate flood impacts. The environmental vulnerability of CC is relatively low (0.162), indicating that environmental degradation is less critical in this area but should not be neglected (Fig 6).

Physical FVI of Study area and Sub-regions RM, RC and CC

The Physical Flood Vulnerability Index (PhFVI) is a targeted analytical tool dedicated to quantifying the inherent susceptibility of the built environment primarily structures, infrastructure, and property to damage from flood events.

$$FVI\ (Physical - study\ area) = \frac{0.394 * 0.366 * 0.347 * 0.184}{0.359} * 10 = 0.256$$

$$FVI\ (Physical - RM) = \frac{0.756 * 0.359 * 0.347 * 0.189}{0.314} * 10 = 0.566$$

$$FVI\ (Physical - RC) = \frac{0.2 * 0.4 * 0.35 * 0.203}{0.290} * 10 = 0.196$$

$$FVI\ (Physical - CC) = \frac{0.548 * 0.236 * 0.34 * 0.181}{0.309} * 10 = 0.257$$

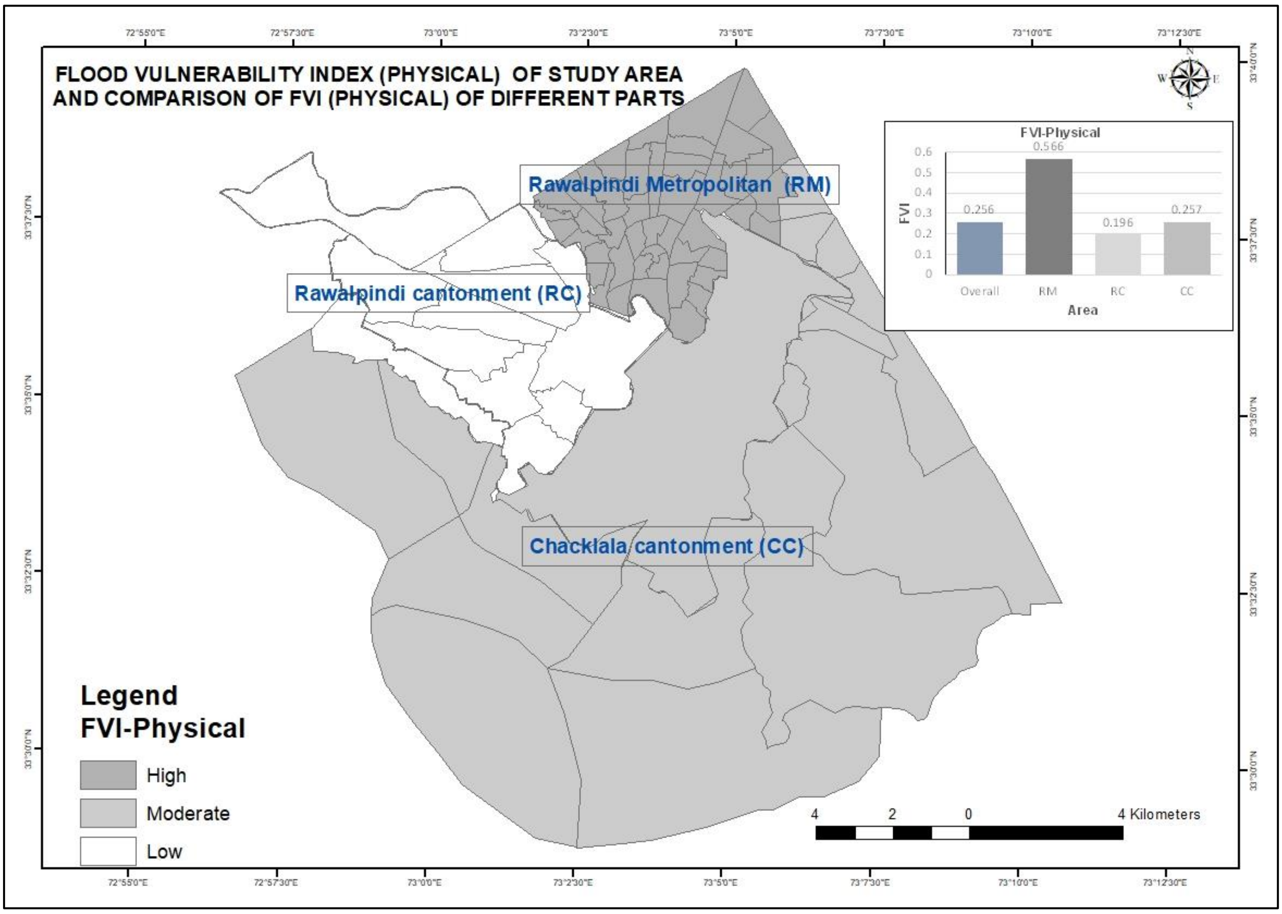

Fig 7: Map showing FVI (Physical) of Study area and its Sub-regions RM, RC and CC

The physical components of study area, with FVI values of 0.256, further underscore the area's exposure to flood risks across multiple dimensions. The physical dimension of RM also demonstrates significant vulnerability, with an FVI (Physical) of 0.566. This suggests that the area's infrastructure and built environment are highly susceptible to flood impacts. The relatively low physical vulnerability (0.196) of RC implies that infrastructure in the cantonment area is comparatively robust but should still be maintained and improved. Again FVI Physical of Chcacklala Cantonment is higher than RC. Although the physical vulnerability (0.257) is moderate, highlighting the importance of maintaining and improving infrastructure to withstand flood events (Fig 7).

Comparison of Cumulative and Component's FVI of Major divisions

The cumulative FVI of whole study area and its division like RMC, Rawalpindi cantonment and Chacklala cantonment were calculated. The cumulative FVI is average of Social, economic, environment and Physical FVIs. The overall FVI of the study area was 0.42, referring to table 2, the area falls in upper edge of the vulnerability. If we observe the constituents of the FVI, the value of

FVI (Social) is 0.62, means highly vulnerable to urban flooding. As far as the FVI (environment) is concerned, again 0.432 having upper edge of the vulnerability. Whereas, FVI Economic and Physical are having 0.375 and 0.256 respectively again confirm these divisions of the areas are vulnerable to the flood (Table 2).

Table 2: Flood Vulnerability Index

Serial	Area	FVI (social)	FVI (Eco)	FVI (Environment)	FVI (Physical)	Cumulative FVI
1.	Study area	0.62	0.375	0.432	0.256	0.42
2.	RMC	0.674	0.326	0.435	0.566	0.5
3.	Rawalpindi cantt	0.491	0.61	0.333	0.196	0.4
4.	Chacklala cant	0.592	0.443	0.162	0.257	0.363

Cross-Area Comparison of Cumulative FVI Values of RM, RC and CC

A direct comparison of the cumulative FVI values reveals a distinct hierarchy of overall flood vulnerability among the studied areas. RM records the highest cumulative FVI at 0.5, placing it in the High vulnerability to flood category. The broader Study area (0.471), Rawalpindi Cantt (0.4), and Chacklala Cantt (0.363) all fall under the Vulnerability to floods category, with Chacklala Cantt exhibiting the lowest overall vulnerability. This gradient suggests varying levels of preparedness, infrastructure, or socio-economic conditions across these administrative boundaries. The fact that RM is categorized at a higher qualitative level High vulnerability compared to the others Vulnerability indicates that it faces a more pressing and severe overall flood risk, likely due to a confluence of factors that make it disproportionately susceptible. Furthermore, the Study area's cumulative FVI of 0.471 is notably close to the 0.5 threshold that defines High vulnerability. This proximity suggests that the Study area is on the cusp of a more severe classification, implying that its current Vulnerability status is precarious. Even a slight increase in any contributing vulnerability factor, or a lack of proactive intervention, could easily elevate its risk profile, underscoring the urgency for preventive actions.

Comparative Analysis of Specific FVI Components of RM, RC and CC

While the overall cumulative FVI values show variation, a comparative analysis of individual FVI components across all areas reveals both consistent patterns and significant heterogeneity. The most striking finding is the consistently high social vulnerability observed across whole study areas. The FVI (social) values are 0.62 for the Study area, 0.674 for RMC, 0.491 for Rawalpindi Cantt, and 0.592 for Chacklala Cantt. All these values fall within the "High vulnerability to flood" range. This consistency, irrespective of the overall cumulative FVI or variations in other components, points to a fundamental and widespread issue related to the social dimension of flood vulnerability across the entire study region. This suggests that socio-economic factors, community preparedness, or demographic characteristics represent a systemic weak point in the region's flood resilience, demanding region-wide policy attention rather than localized efforts alone.

In contrast to the uniform social vulnerability, there is significant heterogeneity in economic, environmental, and physical vulnerabilities across the areas. For instance, the FVI (Eco) varies from a low of 0.326 for RM (vulnerability to flood) to a high of 0.61 for Rawalpindi Cantt (Vulnerability). Environmental vulnerability ranges from 0.162 for Chacklala Cantt ("Small vulnerability") to 0.496 for the "whole Study area" (Vulnerability). Similarly, physical vulnerability shows wide variation, from 0.196 for Rawalpindi Cantt (Small vulnerability) to 0.566 for RM ("High vulnerability"). This variation indicates that while regional social strategies are universally needed, interventions for other factors must be carefully tailored to the specific strengths and weaknesses of each administrative division. A one-size-fits-all approach for these components would be ineffective; instead, localized assessments and bespoke solutions for infrastructure, economic diversification, and environmental management are necessary.

Discussion and Conclusion

This study assessed the flood vulnerability of Rawalpindi city, focusing on its three major administrative sub-regions: Rawalpindi Metropolitan (RM), Rawalpindi Cantonment (RC), and Chacklala Cantonment (CC). The Flood Vulnerability Index (FVI) was calculated for each division, as well as for their respective social, economic, environmental, and physical sub-components. The results reveal that all three sub-regions exhibit moderate to high levels of flood vulnerability, with RM displaying the highest overall FVI (0.5), followed by Rawalpindi Cantonment (0.4), and Chacklala Cantonment (0.363). The social dimension consistently emerged as the most significant contributor to vulnerability across all sub-regions, with the highest FVI (Social) observed in RM (0.674) and Chacklala Cantonment (0.592). These findings underscore the critical role of socio-economic factors such as poverty, lack of awareness, and inadequate community preparedness in shaping flood risk in urban contexts. Economic vulnerability was also found to be substantial, particularly in Rawalpindi Cantonment (0.61), highlighting the impact of income instability, limited financial resources, and livelihood insecurity on flood resilience. Environmental and physical vulnerabilities varied across regions, with generally lower indices in Chacklala Cantonment, possibly reflecting relatively better infrastructure and environmental management in that area. The spatial variation in flood vulnerability across Rawalpindi's divisions can be attributed to differences in settlement patterns, infrastructure quality, population density, and local governance. Unplanned urban expansion, encroachment on natural drainage channels, and the proliferation of impervious surfaces were identified as key drivers of increased flood risk, consistent with findings from previous studies e.g. (Zeleňáková et al., 2017; Zhou et al., 2019). Importantly, the study highlights the cyclical nature of vulnerability in low-income communities, where repeated flood events erode resilience and exacerbate existing socio-economic challenges. The limited capacity of local institutions and the lack of effective early warning and disaster management systems further compound these risks.

This research provides a comprehensive assessment of flood vulnerability in Rawalpindi, utilizing the Flood Vulnerability Index (FVI) as a multidimensional tool to capture the complex interplay of social, economic, environmental, and physical factors. The findings indicate that Rawalpindi's urban areas, particularly the historic core and cantonment zones, are moderately to highly vulnerable to flooding, with social and economic factors being the predominant contributors.

Recommendation: following actions are recommended to mitigate the flood affects in study area:

Public Awareness: Develop and implement region-wide public awareness campaigns on flood safety, risk perception, and preparedness measures.

Coordinated Early Warning: Establish a coordinated regional early warning system with clear communication protocols and accessible channels to ensure timely dissemination of information to all communities.

Social Infrastructure: Invest in social infrastructure, such as community centers and accessible shelters that can serve as safe havens and coordination points during flood events.

Targeted Interventions: There is a pressing need for targeted interventions to enhance community awareness, improve socio-economic conditions, and strengthen local capacities for disaster preparedness and response.

Infrastructure Upgrades: Investments in drainage systems, flood defenses, and resilient infrastructure are essential to reduce physical vulnerability, particularly in densely populated and low-lying areas.

Integrated Urban Planning: Urban growth management policies should prioritize the protection of natural drainage channels, restrict settlement in high-risk floodplains, and promote sustainable land use practices.
Institutional Strengthening: Enhanced coordination among local government agencies, improved early warning systems, and community-based disaster risk reduction initiatives are critical for building urban resilience.
In conclusion, the application of the FVI framework offers valuable insights for policymakers, urban planners, and disaster management authorities. By identifying the most vulnerable areas and underlying drivers of flood risk, this approach supports the development of effective, evidence-based strategies to mitigate the impacts of urban flooding and promote resilient urban development in Rawalpindi and beyond. Other recommendations are as follow:-

- Basing on water level during and after flood, mapping of inundated streets is recommended.
- Helpline numbers and social media campaign viz-a-viz community center to create awareness.
- Annual geo data base of building damage and other damages be prepared.
- A comprehensive campaign of solid waste management be launched. Government of Punjab has already launched (صاف ستھرا پنجاب), it is a good step, same be executed in true letter and spirit.
- Rawalpindi Development authority and cantonment board, are responsible to implement building by laws. They must ensure their implementation in true letter and spirit.
- Public awareness is top most step to make them aware about challenge of flood and role they play to mitigate.
- Interest free flood loans may be introduced.
- Government buildings like School buildings etc. may be reshaped to become help center during and after flood.
- Dredging of stream be carried out in true letter and spirit.
- GIS maps of sewerage lines network of Rawalpindi city are being prepared by WASA. Cantonments to also take initiative and prepare sewerage maps.
- Elaborated maps of hotspot area be prepared for institutions and community awareness.
- PMD has warning system but limited to adjacent areas of Nullah Lai. Other sources, most important of mosque may be used for early warning of flood.
- A monitoring policy to control encroachment and proper disposal of garbage is to be checkout and executed in true letter and spirit.
- Community focal groups be nominated for better communication between community and institutions.
- On the base of FVI, most vulnerable area is RM followed by Chaklala and Rawalpindi Cantonments. The index of other areas may be computed. On the basis of FVI, areas may be ranked for essential pre and post flood support.
- Expansion of spongy surface in the term of green patches is very important to absorb the overflow streams and rainfall water. It can only be done with the strict implementations of building by-laws.

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