FLOOD RISK ASSESSMENT OF THE WALLED CITY OF JAIPUR

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Jaipur, India

About the Research Paper

The research paper presents a preliminary analysis which is conducted, using Quantum Geographic Information System (QGIS), an open software, to map and evaluate factors contributing to flood vulnerability in the Walled City of Jaipur. The study focuses on the Walled City of Jaipur, where frequent monsoonal flooding poses risk of rain water flooding. The paper emphasises on the importance of meticulous planning and preparedness for effective flood risk management.

The research paper is focuses on developing a flood risk map to tackle the challenges posed by seasonal floods in the Walled City of Jaipur. Such mappings can be crucial for effective disaster management and preparedness in regions prone to seasonal flooding. By integrating data, models, and analysis techniques, such mappings can help the authorities make informed decisions, allocate resources efficiently, and mitigate the impact of floods on communities and infrastructure.

Feedback

We strive for constant improvement and encourage our readers to provide their valuable feedback/suggestions. Please send us your suggestions and comments about this Research Paper to iced@cag.gov.in

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Declaration by the Research Associate

I, **Dr. Mahesh Kumar Saini,** hereby declare that the Research Paper titled "**Flood Risk Assessment of the Walled City of Jaipur"** submitted to iCED, Jaipur is my own work, and no part of it has been published anywhere else in the past. The facts and figures given in the paper are authentic to the best of my knowledge.

I concur with the modifications/corrections carried out during the report evaluation based on inputs provided by me.

2 July 2024 **(Dr. Mahesh Kumar Saini)**
Jaipur **Research Associate, iCED**

Acknowledgement

I wish to express my deepest gratitude and sincere thanks to Ms. Sayantani Jafa, Additional Deputy Comptroller and Auditor General and Director General, iCED for giving her invaluable guidance throughout the research work.

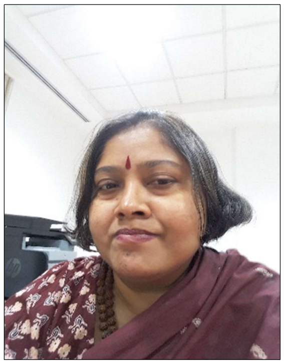
I would like to express my sincere gratitude to Dr. Nanda Dulal Das, Former Director (Training and Research), iCED and Shri Mehul Grover, Director (Training and Research), iCED for his invaluable supervision, guidance, and constructive suggestions during my project research experience.

I also extend my sincere thanks to Shri Anupam Srivastava, Senior Administrative Officer, iCED, for his valuable input and feedback.

In conclusion, I extend my heartfelt thanks to Shri Manoj Kumar, Assistant Administrative Officer, iCED, for generously sharing his valuable knowledge. His unwavering support, constructive feedback, and constant encouragement throughout my research work on the paper have left an indelible mark on my academic journey.

2 July 2024 **(Dr. Mahesh Kumar Saini)**
Jaipur **Research Associate, iCED**

Foreword



Climate Change has become a real and tangible issue confronting the world; and as such requires a paradigm shift in understanding its ramifications. Within this context, the Supreme Audit Institutions (SAIs) have played a crucial role by focussing on environmental governance, requiring a multifaceted approach beyond conventional techno-think in isolation from other aspects.

Under the aegis of the Comptroller and Auditor General of India the International Centre for Environment Audit and Sustainable Development (iCED), Jaipur is at the forefront of a collaborative framework for knowledge exchange and best practices sharing among public auditors on environmental issues.

Since 2022, iCED has formulated an Occasional Research Paper (ORP) Series to study environmental challenges, such as Climate Change, ocean acidification, urban flooding, and municipal solid waste management. This is the 14th volume in iCED's ORP Series.

The preliminary findings from the iCED's study of "Flood Risk Assessment of the Walled City of Jaipur" demonstrates the use of the Geographic Information System (GIS) and Remote Sensing techniques such as the Quantum Geographic Information System (QGIS) to evaluate and understand potential flood risks faced by ancient cities such as the Walled City of Jaipur. This data-driven approach aims to identify flood-prone areas for the Walled City of Jaipur, paving the way for informed decision-making and the development of effective mitigation and preparedness strategies.

This paper represents a significant milestone in advancing our understanding of the GIS and Remote Sensing tools and their use in conducting audits, its audit complexities, underscoring iCED's commitment to serving as a specialised hub for conducting rigorous in-house research under the Comptroller and Auditor General of India.

2 July 2024

Jaipur

(Sayantani Jafa)

Additional Deputy C&AG and Director General, iCED

Message from the Director (Training and Research)

I am pleased to unveil the initial findings from our recent scientific investigation, entitled "Flood Risk Assessment of the Walled City of Jaipur". This research signifies a significant advancement in our commitment to employing state-of-the-art Geographic Information System (GIS) methodologies for a comprehensive assessment of potential flood risks confronting the culturally enriched city of Jaipur.

Our research team has meticulously conducted this preliminary analysis, utilising the advanced functionalities of Quantum Geographic Information System (QGIS) to map and evaluate diverse factors contributing to flood vulnerability in the old city. The amalgamation of spatial data, topographical information, and hydrological parameters has empowered us to offer valuable insights into areas susceptible to flooding. The findings, delineated in this report, are envisaged to serve as a foundational resource for informed decision-making in the formulation of strategies for flood mitigation and preparedness.

I extend my sincere gratitude to Ms. Sayantani Jafa, Additional Deputy Comptroller and Auditor General and Director General, iCED, for her exceptional leadership and unwavering support during this scientific inquiry. Her dedication has played a pivotal role in bringing this study to fruition.

I also wish to acknowledge and express appreciation to all individuals, both directly and indirectly engaged in the creation of this scientific document. Through their collaborative efforts, we have produced a document that lays the groundwork for more in-depth assessments and policy considerations, directed at safeguarding the heritage and inhabitants of Jaipur from the challenges posed by flood risks.

I am confident that this Scientific Research Paper will not only contribute significantly to the scientific discourse on Flood Risk Assessment of the Walled City of Jaipur but will also find applications across diverse audit stages, particularly within the domain of species conservation. I eagerly anticipate the continued success of our scientific research initiatives and their positive influence on environmental auditing and sustainable development.

2 July 2024 **(Mehul Grover)**

Jaipur Director (Training and Research), iCED

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Abbreviations

CWC	:	Central Water Commission
DEM	:	Digital Elevation Model
FCMP	:	Forest Carbon Monitoring Programme
FEI	:	Flood Exposure Index
FHI	:	Flood Frequency Index
FRI	:	Flood Risk Index
FVI	:	Flood Vulnerability Index
GIS	:	Geographic Information System
IFSAR	:	Interferometric Synthetic Aperture Radar
IMD	:	India Meteorological Department
MoEFCC	:	Ministry of Environment, Forest and Climate Change
NDMA	:	National Disaster Management Authority
NIA	:	National Institute of Ayurveda
NRSC	:	National Remote Sensing Centre
OECD	:	Organisation for Economic Cooperation and Development
QGIS	:	Quantum Geographic Information System
SPI	:	Stream Power Index
STI	:	Sediment Transport Index
TRI	:	Topographic Roughness Index

Flood Risk Assessment of the Walled City of Jaipur

1. Introduction

The Indian subcontinent, due to its unique geographical and climatic conditions, is highly susceptible to flooding. According to the Organisation for Economic Cooperation and Development (OECD), floods are amongst the most prevalent, extensive, and catastrophic natural disasters effecting an estimated 250 million people and causing annual losses of USD 40 billion. The growing concentration of assets in floodplains and coastal areas, coupled with the anticipated effects of Climate Change on precipitation patterns and sea levels, is likely to result in escalating losses in the future (OECD, 2016).

Floods are a recurring phenomenon that wreaks havoc on lives and livelihoods, causing immense damage to property, infrastructure, and public utilities. As per the Comptroller and Auditor General’s Audit Report on “Schemes for Flood Control and Flood Forecasting”, the report (December 2006) of the Working Group on Flood Control Management Programme's (FCMP) for the XIth Five Year Plan (2007-2012), an average of 7.55 Million hectares (Mha) of land is affected annually, resulting in a loss of 1,560 lives and economic losses estimated at ₹ 1,805 crore due to damage to crops, homes, and public utilities (CAG, 2017).

As per the NITI Aayog Report submitted by the Committee Constituted for Formulation of Strategy for Flood Management Works in Entire Country and River Management Activities and Works Related to Border Areas (2021–2026), the Rashtriya Barh Ayog (RBA, 1980) estimates that 40 Mha of land are prone to floods. Out of this area, approximately 21 Mha can be protected from flooding to a reasonable degree. Based on available data, it is estimated that 7.17 Mha of land is affected by flood annually, with 3.94 Mha of this area being cropland. On an average, floods claim the lives of 1,654 humans and 618,248 cattle each year. Additionally, around 1.2 million houses are damaged by floods annually, resulting in average monetary losses of ₹ 5,649 crore (NITI Aayog, 2021).

Urban Flood Risk in India

In recent times, urban flooding has emerged as a new form of seasonal floods-especially in urban areas with high density of inhabitants, congested building forms, and limited water exit points. India is home to many historic cities that have been constructed by the erstwhile rulers that have now become a major victim of urban floods due to the growing number of inhabitants and increased frequency and volume of seasonal rainfall patters due to Climate Change.

Urban flooding is significantly different from rural flooding as urbanisation leads to developed catchments, which increases the flood peaks from 1.8 to 8 times and flood volumes by up to 6 times. Consequently, flooding occurs very quickly due to faster flow times (in a matter of minutes). Urban areas are densely populated and people living in vulnerable areas suffer due to flooding, sometimes resulting in loss of life. It is not only the event of flooding but the secondary effect of exposure to infection also has its toll in terms of human suffering, loss of livelihood and, in extreme cases, loss of life. Urban areas are also centres of economic activities with vital infrastructure which needs to be protected 24 x 7. In most of the cities, damage to vital infrastructure has a bearing not only for the state and the country but it could even have global implications. Major cities in India have witnessed loss of life and property, disruption in transport and power and incidence of epidemics. Therefore, management of urban flooding has to be accorded top priority. The increasing trend of urban flooding is a universal phenomenon and poses a great challenge to urban planners the world over. Problems associated with urban floods range from relatively localised incidents to major incidents, resulting in cities being inundated from hours to several days. Therefore, the impact can also be widespread, including temporary relocation of people, damage to civic amenities, deterioration of water quality and risk of epidemics.

It is essential to have effective strategies for reducing the risk of flood disasters in urban areas especially in cities with high habitation density and urbanisation. The technology of Remote Sensing and Geographic Information System (GIS) can act as an invaluable tool in hazard management, offering a comprehensive and accurate assessment of hazard footprints. Satellite data, with its high-resolution capabilities, provides detailed insights into the impact of hazards, enabling effective mitigation strategies. Remotely sensed optical and microwave data can be analysed to assess the severity and extent of the flood damage, facilitating timely response and recovery efforts. Over the past two decades, numerous studies (Panhalkar, 2017; Siddayao, 2014; Masood, 2012; Wang, 2011; Suthakaran, 2022; Sansare, 2020; Lyu, 2018; Cai, 2019; Osman, 2023) have utilised remote sensing data to accurately map flood inundation areas and monitor flood dynamics, providing crucial information for hazard management and risk reduction strategies.

This Research Paper uses Quantum Geographic Information System (QGIS) for mapping flood risk areas in the Walled City of Jaipur. The approach involves creating a framework to depict flood hazard, exposure, and vulnerability with spatial precision, and integrating this information into a comprehensive flood risk map.

2. Material and Methods

2.1 Study Area: The Walled City of Jaipur

The study area, for the Research is the Walled City of Jaipur- also known as Heritage Jaipur (Figure 1). The study area is located between 26° 55' 27.4" N and 75° 49' 18.7" E, nestled amidst the Aravalli hill ranges at an altitude of approximately 430 metres above sea level. Part of the Jaipur district in the north-eastern region of Rajasthan, the city spans around 710 hectares (Jaipur World Heritage, 2024).

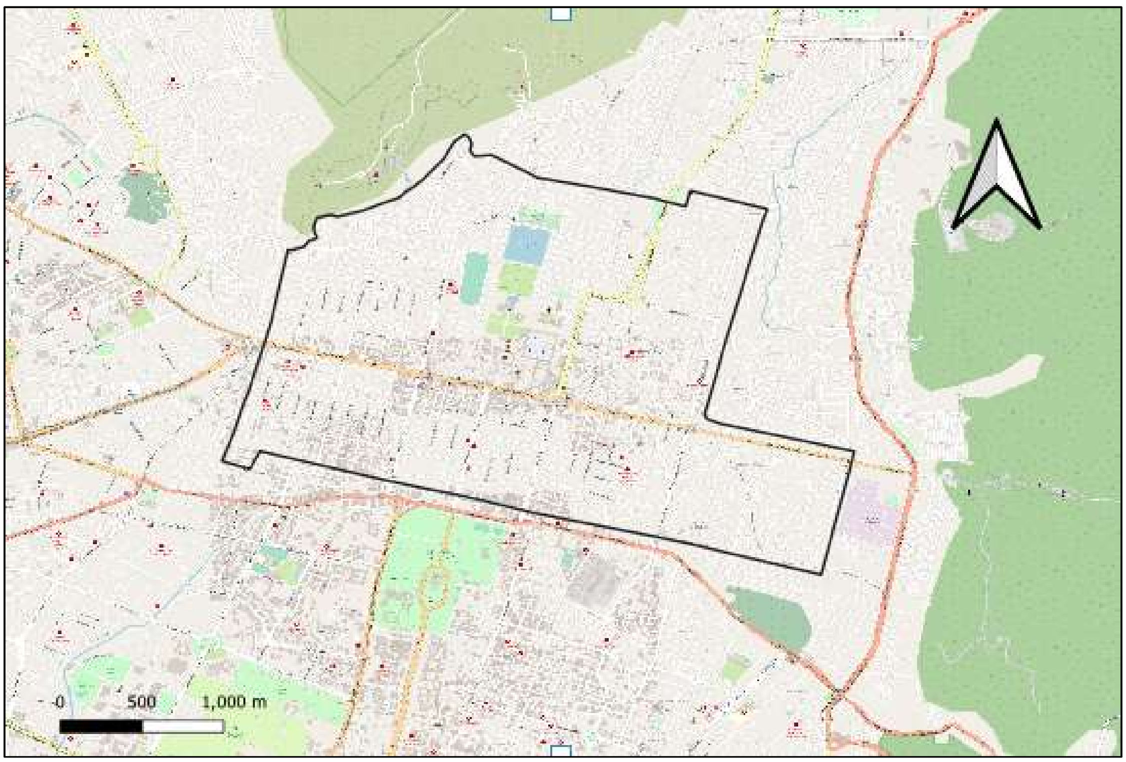

Figure 1: The Walled City of Jaipur Map (Map not to scale) Source: JDA, Jaipur (JDA, 2020)

The Walled City of Jaipur is located in a semi-arid region and experiences rainfall in the monsoon season from July to September. Among the important cities of India, the average annual rainfall varies from 2932 mm in Goa and 2401 mm in Mumbai on the higher side, to 669 mm in Jaipur on the lower side (NDMA Govt. of India, n.d.). In 1757, Jaipur experienced a severe flood that caused widespread damage and loss of life. Since then, there have been numerous other floods, including in 1981, 2016, 2020, 2021 and 2023 as shown in Table 1 below. In recent years, the probability of floods in Jaipur has increased due to a number of factors such as high-intensity rainfall spells due to Climate Change, and poor drainage systems (IMD, 2020; Willems, 2012).

Rapid urbanisation is also contributing to the flood risk in Jaipur (IMD, 2021). As the city grows, more and more land is being covered by impervious surfaces, such as concrete and asphalt (Chithra, 2015). This reduces the amount of water that can be absorbed into the ground, which increases the runoff and risk of flooding (Qin, 2020). Poor drainage systems are another factor that contributes to the flood risk in Jaipur (Tomar, 2021). Thus, heavy rainfall has become a major factor for the increased flood risk in Jaipur city.

However, the consistent occurrence of floods during the monsoon season raises major concerns regarding efficient disaster management which requires a systematic approach to address the impacts of these events.

Table 1: Major floods chronology in Jaipur

Year	Description	Source
1981	Jaipur witnessed the heaviest rainfall in the last 31 years, with 32.6 centimetres of rainfall in a single day (14 July 2000). This led to severe flooding, inundating low-lying areas and damaging homes and infrastructure.	(Singh, 2015)
2016	Jaipur experienced heavy rainfall for several days in August 2016, leading to widespread flooding in the city and surrounding areas.	(Saini, 2016)
2020	In August 2020, Jaipur was again hit by heavy rainfall, causing flash floods that inundated low-lying areas and damaged homes and infrastructure.	(IMD New Delhi, 2021)
2021	Jaipur experienced heavy rainfall in July 2021, causing flooding in several parts of the city.	(Khandelwal, 2022)
2023	In July 2023, Jaipur was again hit by heavy rainfall, causing flooding in several parts of the city.	(Mit J. Kotecha, 2023)

2.2 Heritage Building Conservation

Heritage building conservation is crucial for preserving the cultural and historical significance of Heritage Jaipur. Jaipur's historical monuments and buildings require conservation efforts to maintain their integrity and beauty, as they are a testament to the city's illustrious past and a source of national pride. Ensuring the preservation of these structures is essential for future generations, the structure of Government organisations shown in Table 2, working for Heritage Jaipur conservation.

Table 2: Heritage Building Conservation

Sector	Planning	Implementation	Operation and maintenance
Heritage Building Conservation	JDA, JNN, RUIDP, PHED, DD, PriOwn	JDA, JNN, RUIDP, PHED, DD, PriOwn, SpSo	JDA, JNN, PHED, DD, PriOwn, SpSo

Where: JDA: Jaipur Development Authority, JNN: Jaipur Nagar Nigam, RUIDP: Rajasthan Urban Infrastructure Development Project, DD: Devasthan Department, PHED: Public Health Engineering Department, PriOwn: Private Owner, SpSo: Special Societies

2.3 Flood Risk Assessment

According to Kron, 2005 and Zhang, 2020 the Flood Risk Index (FRI) can be prepared as per the given formula 1, by the combination of three parameters Exposure, Hazard, and Vulnerability.

$$\boldsymbol{FRI = FHI \times FEI \times FVI} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{1}$$

$$(\text{Kron}, 2005;\ \text{Zhang}, 2020)$$

Where:

FRI = Flood Risk Index
FHI = Flood Hazard Index
FEI = Flood Exposure Index
FVI = Flood Vulnerability Index

In this study, we have used the above formula to prepare the Flood Risk Map for the Walled City of Jaipur.

2.3.1 Flood Hazard Index

A Flood Hazard Index (FHI) is a spatial tool used to assess the relative susceptibility of an area to flooding. It is an open-street-based data that incorporates multiple factors such as buildings, highways, road lines, metro lines and other buildings, etc. that contribute to the flood hazard map. Historical trends in flooding are important for understanding the current risk and what might happen in the future (Klijn, 2008). As field data are scattered and difficult to obtain in Old City Jaipur, remote sensing tools have been used to derive the required data for estimating the FHI. Some of the parameters utilised in preparing the FHI are given below:

Infrastructure plays a crucial role in reducing the risks associated with disasters, as any failure or decline in capacity can directly impact the community (Cantillo, 2019). The focus for FHI preparation involves key components such as buildings, metro lines, highways, roads, and other significant structures (hospitals, temples etc.).

Roads and highways are vital for facilitating the movement of goods and services, serving as the community's lifeline and enabling timely evacuations during emergencies.

Metro lines, particularly in urban areas, constitute an essential transportation system. Critical structures like hospitals provide crucial support during crises, offering relief to affected individuals in the vicinity.

Buildings such as houses, schools, temples etc. can also serve as shelters when building integrity is compromised during floods (Sebring, 2000).

All indicators for this assessment have been derived from the Open Street Map. The process involves extracting building types, Highways, and road networks from Open Street Map data by generating geometric attributes, enriching buildings with road categories, creating buffers around roads, and exporting the desired map area as an Open Street Map file, by using QGIS.

Figure 2: Road lines of the Walled City of Jaipur

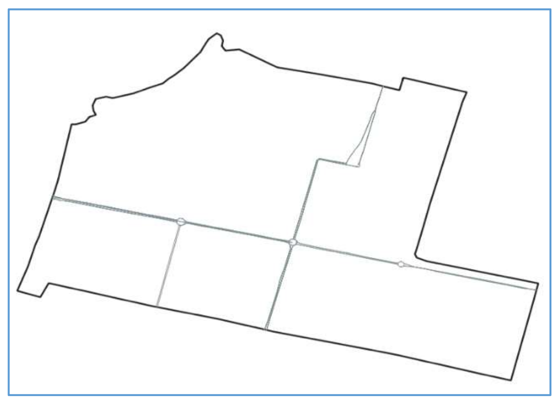

Figure 3: Highways of the Walled City of Jaipur

Figure 4: Buildings in the Walled City of Jaipur

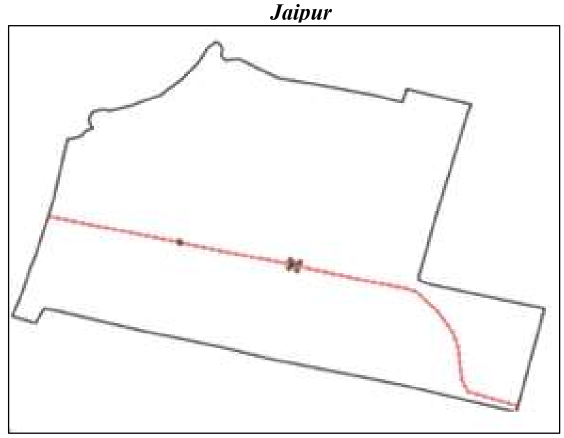

Figure 5: Metro-line in the Walled City of Jaipur

Figures 2, 3, 4 and 5 have been prepared using QGIS and are based on Open Street Map of Walled City of Jaipur (Map not to scale).

2.3.2 Flood Exposure Index

A Flood Exposure Index (FEI) is a quantitative measure that assesses the potential damage or harm that floods can cause to people, property, and infrastructure within a given area. It is calculated by considering various factors such as altitude, aspect, slope, curvature etc. For these factor's data extraction Digital Elevation Model has been used in the Research Paper.

Digital Elevation Model

The Digital Elevation Model (DEM) is also known Digital Terrain Model (DTM) and Digital Surface Model (DSM). A DEM is a 3D computer graphics representation of elevation, slope, and hill shade data used to depict terrain or overlaying surfaces (USGS, n.d.). DEMs provide detailed information about the terrain, aiding in better decision-making and planning through accurate visualisation of the landscape (Mukherjee, 2013; Scholtes, 2013).

The DEM was generated using Interferometric Synthetic Aperture Radar (IFSAR) images with a pixel size of 5 m x 5 m, obtained in 2014 (Sukojo, 2021). From this DEM various key topographical characteristics such as elevation, slope, aspect, curvature, Sediment Transport Index (STI), Stream Power Index (SPI), Topographic Wetness Index (TWI), and Topographic Roughness Index (TRI) can be derived (Rabby, 2020).

In this study we are using elevation, slope and hill shade indicators by the DEM model to assessment the FEI.

Elevation, Slope and Hill shade are particularly crucial in flood studies, as research suggests that elevated areas are less likely to experience flood events (Botzen WJW, 2012). Typically, water flows from higher to lower terrains, making flat regions more vulnerable to flooding. Additionally, topographical factors influenced by the flow extent and runoff speed play a significant role in determining the likelihood of floods (Kia MB, 2011). The DEM serves as a vital source for extracting each topographical parameter associated with flood occurrence in a specific area.

The DEM preparation for the current study has been done in the QGIS (open source) using tools such as "Raster > Extraction > Contour", "Raster > Analysis > DEM (Terrain models)", or "Raster > Analysis > Grid (Interpolation)" for observing Elevation, Slope, and Hill shade in the required DEM model.

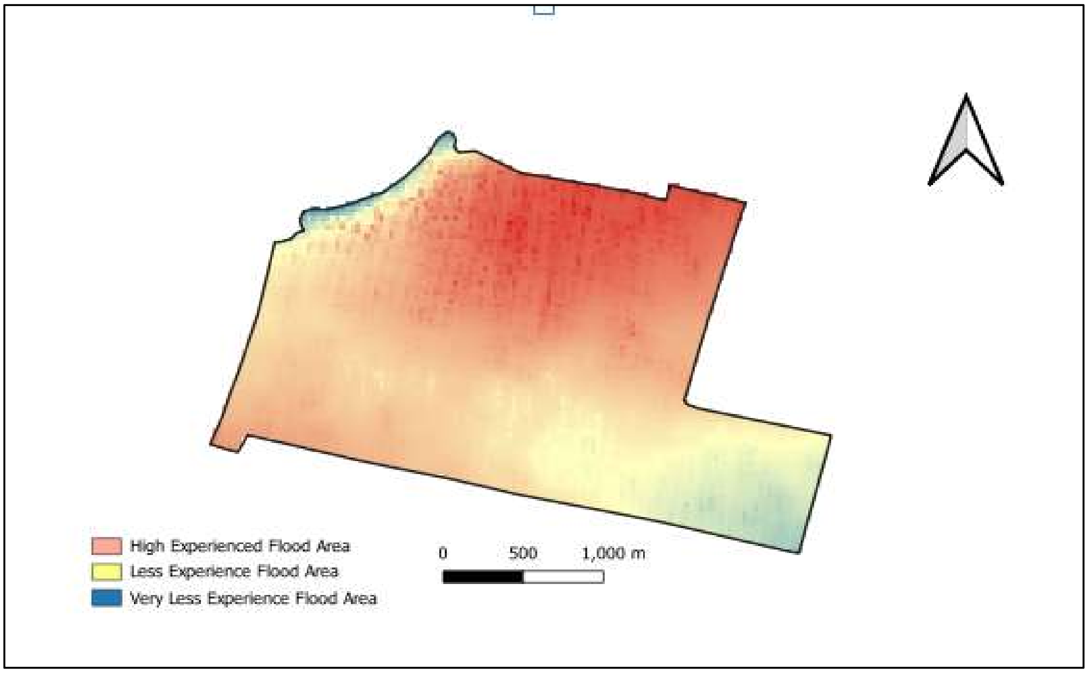

Figure 6: Digital Elevation Model of the Walled City of Jaipur (Map not to scale)

2.3.3 Flood Vulnerability Index

A Flood Vulnerability Index (FVI) is a spatial measure that assesses the susceptibility of a region to flood damage. FVIs are used to inform flood risk management and mitigation strategies, as well as to identify areas that are most at risk of flood damage. Vulnerability reduction and increasing resilience are key components in disaster risk reduction. The first step is to analyse the current vulnerability of a community, township, or region to floods. However, there are a wide variety of definitions of vulnerability including a variety of different indicators (Cannon, 1994; Balica, 2010; Borden, 2007).

This Research Paper utilises two main indicators namely the Precipitation Volume and the Population present in a risk area. The data on other indicators was found to be scarce.

Precipitation volume has been calculated by using the zonal statistics in QGIS software.

Population data has been extracted from the layer selected from link (https://crudata.uea.ac.uk/cru/data/hrg/ cru_ts_4.05/cruts.2103051243. v4.05/ pre/). These layers are utilised to form a flood risk map.

Population

The flooding of densely inhabited regions presents numerous risks, such as the potential for human casualties, property damage, and the transmission of infectious diseases. The assessment of population vulnerability utilised the Worldpop dataset, as outlined by Shokri in 2020 (Shokri, 2020).

WorldPop creates open-access geospatial datasets and peer-reviewed techniques for high-resolution population distributions worldwide. The population densities and counts are displayed in these datasets at grid cell sizes of 1 x 1 km and 100 x 100 m. One can obtain the WorldPop datasets for free from the website for extracting the population statistics. To utilise the datasets using QGIS programs, available for download in a number of formats, including GeoTIFF. One may import the WorldPop raster files into QGIS software, and crop or extract the population data for the Walled City of Jaipur.

On the basis of elevation values, the Walled City of Jaipur was divided into three categories with ranges of 424-428, 428-476 and 476-502. The elevation has a negative relationship with flooding. Areas with low elevation are more likely to experience flooding than areas with high elevation (Ramesh, 2022). The region in red colour has the lowest range of elevation and thus is more vulnerable to fill up first in case of a heavy rainfall. Due to this, the people living in this area are at more risk of flooding.

Based on the WorldPop population data (WorldPop, 2023) for the specified region of Walled City of Jaipur, the total population is 29,75,307. Among them, 7,717 people reside in an area classified as very high risk, 6,849 in a high-risk area, and 11,444 in a low-risk area. The remaining 2,949,297 people live in other parts of the region, also categorised as low-risk area as shown in Figure 7.

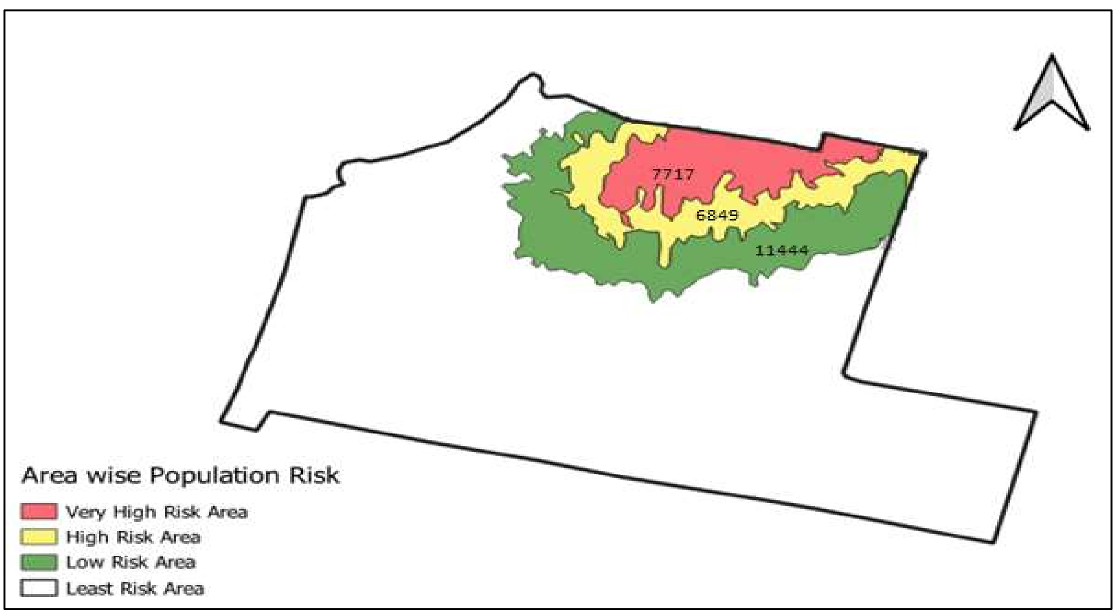

Figure 7: Flood risk area and the affected population in Walled City of Jaipur (Map not to scale)

Precipitation Volume

The straight forward factor of rainfall, indicative of various flood aspects, is a key element in nearly all flood definitions. A meteorological flood is described as a scenario in a region where rainfall significantly exceeds the climatological average. This is due to the natural vegetation and economic activities in the area being adapted to the region's long-term average rainfall (Ologunorisa, 2005). Consequently, flood conditions arise when the rainfall surpasses a specific amount considered normal for that particular region that calculated for the Walled City of Jaipur.

How to measure the Precipitation Volume?

A rain gauge can be used to measure the volume of precipitation. A cylinder with a funnel that feeds water into a measuring flask makes up the basic rain gauge. Precipitation totals are calculated over certain time intervals, such as hourly, daily, weekly, or monthly. To calculate the volume of precipitation in a particular area, the following formula can be used:

$$\mathbf{V = A \times h} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\mathbf{2}$$

Where 'V' is the volume of rainfall, 'A' is the catchment area, and 'h' (Table 3) is the height of the water column (FAO, 1985).

Walled City of Jaipur A = Approx. 6987908 m^2 (Calculated through the QGIS)

The meteorological data from the India Meteorological Department (IMD), Jaipur for the period spanning 2020 to 2022 indicates a notable increase in heavy rainfall occurrences in Jaipur compared to the historical norm. This heightened precipitation has resulted in flooding incidents in the Walled City of Jaipur. Precipitation 2020-2022 observed by IMD office Jaipur, is shown in Table 3:

Table 3: Precipitation in Jaipur from 2020 to 2022

	Year	**Actual rainfall (In mm)**	**Normal rainfall (In mm)**	**Actual rainfall volume (V) (In litres)***	**Normal rainfall volume (V) (In litres)***
Jaipur	2020	566	502.1	3954.64	3508.17
	2021	565.8	502.1	3953.24	3508.17
	2022	652.8	524.3	4561.71	3663.28

Source: Data extracted from the IMDMC Jaipur Annual Report (IMDMC Jaipur, 2020; IMDMC Jaipur, 2021; IMDMC Jaipur, 2022)

*Actual Rainfall Volume and Normal Rainfall Volume calculated by the above formula No. 2.

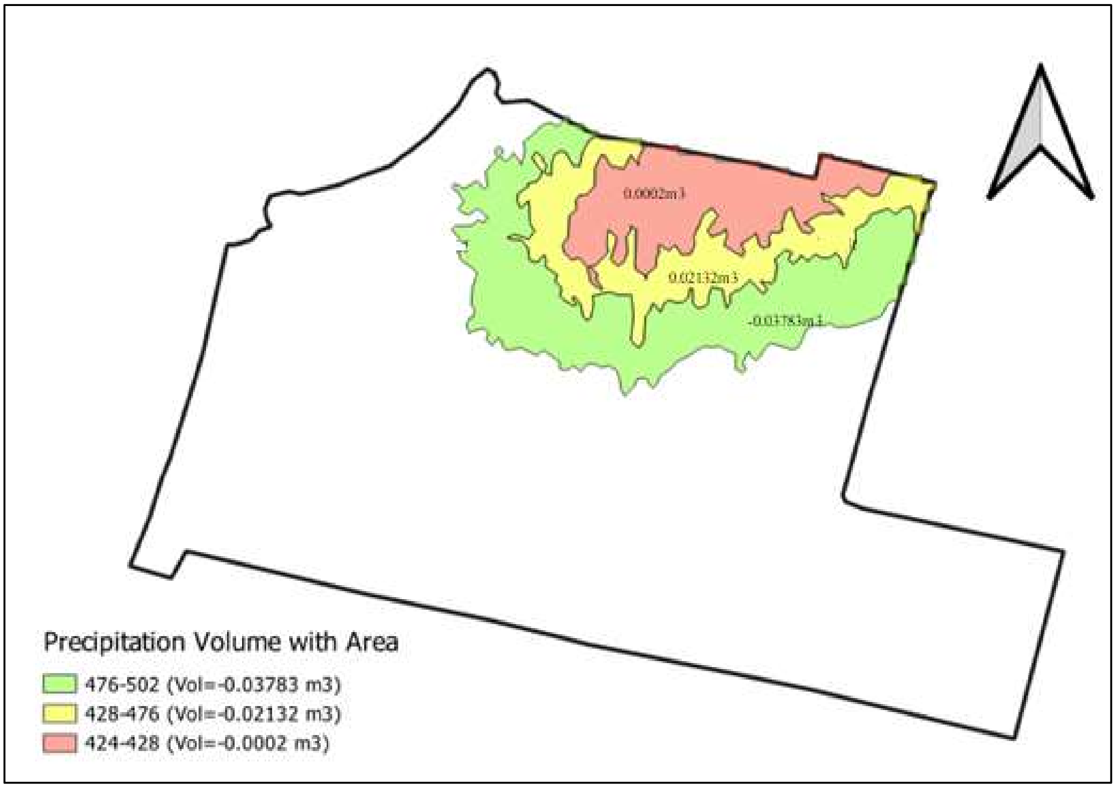

Figure 8: Precipitation volume calculation in a particular area (Map not to scale)

The QGIS-derived zonal statistics reveal that there is a significantly high-risk area spanning 434,467 square metres. This area has a precipitation volume capacity of 0.000025 cubic metres which will be flood first during a heavy rainfall. The rainwater may proceed to the next area (yellow region) as the area can accommodate less volume of water.

Additionally, there is a high-risk area covering 450,369 square metres, and its anticipated precipitation volume is 0.021321569 cubic metres. Furthermore, a low-risk area of 789,426 square metres has a precipitation volume capacity of 0.0378326705 cubic metres. In 2022, Jaipur's precipitation average volume is 524.3 mm which means the average precipitation volume across the specified areas is 0.524 cubic metres as shown in Figure 8.

3. Results and Discussion

In this investigation, we present findings from a study focusing on flood risk assessment in the culturally significant Walled City of Jaipur. The research employed DEM, satellite imagery, and precipitation data to generate detailed flood risk maps tailored to the unique heritage context of Jaipur.

These maps categorised regions based on their susceptibility to flooding, with red designating high-risk areas and blue indicating low-risk zones. The Flood Risk Index map was prepared by combing the FHI = Flood Hazard Index, FEI = Flood Exposure Index, and FVI = Flood Vulnerability Index (Figure 10).

The FRI map points high-risk sites at places such as Chandi Ki Taksal and the National Institute of Ayurveda (NIA). The FRI map can play a pivotal role in emergency response planning by identifying critical infrastructure in safer areas and highlighting locations necessitating enhanced flood protection measures.

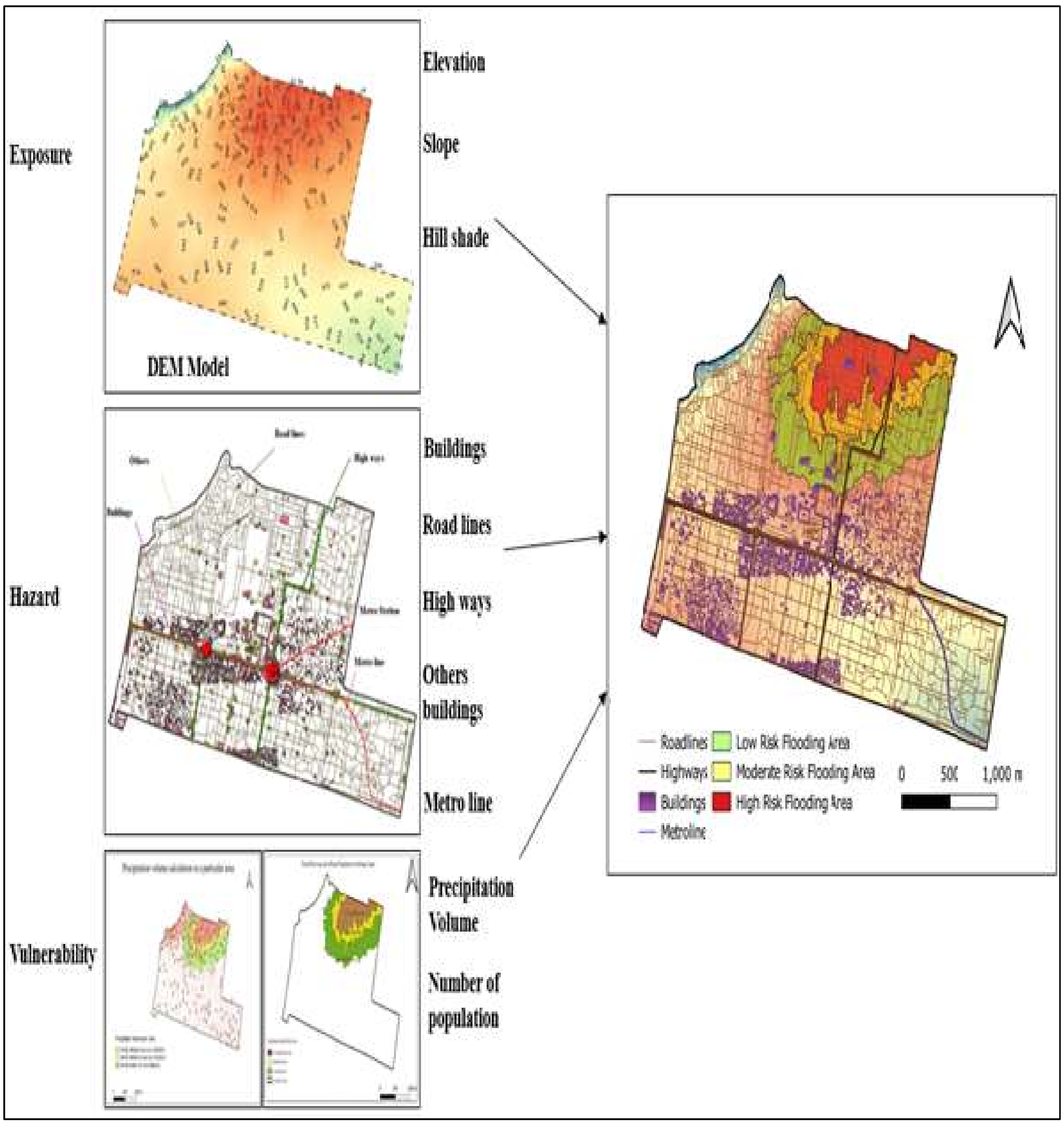

Figure 9: Complete Summary of the Flood Risk Index (Map not to scale)

The FRI Map offers a holistic view of areas prone to recurrent flooding and potential damage. Analysis unveiled a notable surge in intense rainfall events in the Walled City of Jaipur between 2020 and 2022, resulting in heightened flood occurrences. This escalation was linked to factors like escalating urban development and insufficient drainage systems within the region. Examination of precipitation patterns indicated that high-risk zones exhibited a lower capacity to manage the average annual rainfall compared to low-risk regions. The estimated total population in the study area stood at 2,975,307, with approximately 7,717 individuals residing in areas classified as very high risk for flooding. The complete framework for the Flood Risk Index has been explained in Figure 9.

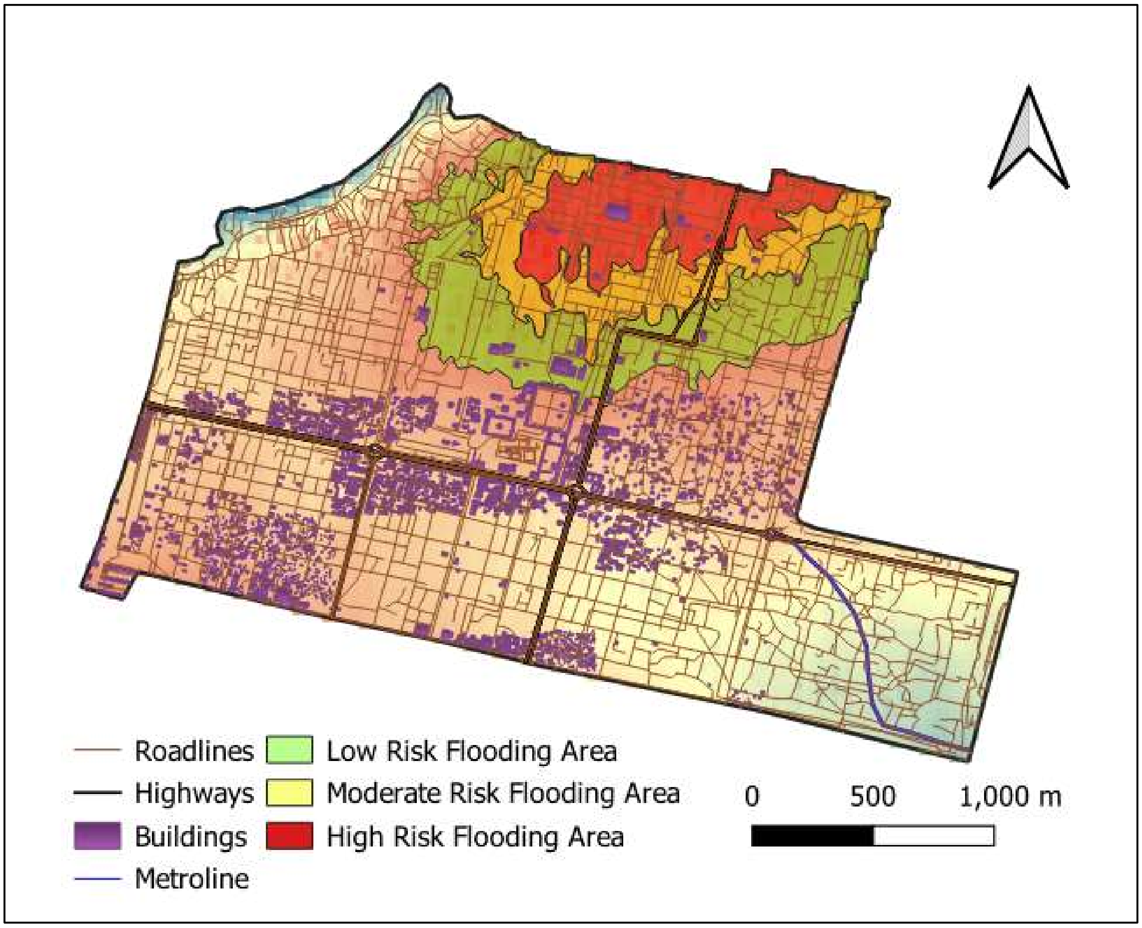

Figure 10: Final Flood Risk Index of the Walled City of Jaipur, prepared by combing the FHI = Flood Hazard Index, FEI = Flood Exposure Index, and FVI = Flood Vulnerability Index (Map not to scale)

Overall, this study underscores the importance of integrating geospatial data, hydrological modeling, and population analysis to formulate robust flood risk assessments essential for guiding emergency preparedness, infrastructure planning, and sustainable urban governance in flood-prone regions like the Walled City of Jaipur.

4. Way forward

The research paper has aimed to address the heightened flood risk in urban areas due to increased precipitation by using GIS and Remote Sensing. The study has employed a QGIS-based risk assessment to identify high-risk areas and proposes interventions such as enhanced storm water management systems and resilient infrastructure. It advocates for the establishment of early warning systems, emergency preparedness plans, and collaborative efforts among governmental agencies, urban planners, engineers, and stakeholders. Furthermore, the integration of Climate Change adaptation strategies into long-term urban planning is emphasised as an essential component. The research offers a comprehensive and scientifically grounded framework for mitigating urban flood risk in the context of heightened precipitation, incorporating advanced methodologies and interdisciplinary collaboration.

Thus, its focus has been on blending climate adaptation and climate mitigation strategies to address the issue of urban flooding challenges. This approach can be a useful modality in assessing audit risk in the concerned sectors.

5. Bibliography

Balica, S. a. (2010). Reducing the complexity of the flood vulnerability index. *Environmental hazards*, 321-339. Retrieved from https://www.tandfonline.com/doi/abs/10.3763/ehaz.2010.0043

Borden, K. S. (2007). Vulnerability of US cities to environmental hazards. *journal of Homeland Security and Emergency Management*, 2. Retrieved from https://www.researchgate.net/profile/Chris-Emrich/publication/40822673_Vulnerability_of_US_Cities_to_Environmental_Hazards/links/560d39b208ae6cf681537785/Vulnerability-of-US-Cities-to-Environmental-Hazards.pdf

Botzen WJW, A. J. (2012). Individual preferences for reducing flood risk to near zero through elevation. *Mitig Adapt Strateg Glob Change*, 229–244. doi:10.1007/s11027-012-9359-5

CAG. (2017). *Schemes for Flood Control and Flood Forecasting.* Delhi: CAG. Retrieved from https://cag.gov.in/webroot/uploads/download_audit_report/2017/Report_No.10_of_2017_-_Performance_audit_Union_Government_Schemes_for_Flood_Control_and_Flood_Forecasting_Reports_of_Ministry_of_Water_Resources,_River_Development_&_Ganga_Rejuven.pdf

Cai, T. L. (2019). Flood risk assessment based on hydrodynamic model and fuzzy comprehensive evaluation with GIS technique. *International Journal of Disaster Risk Reduction*, 101077. doi:10.1016/j.ijdrr.2019.101077

Cannon, T. (1994). Vulnerability analysis and the explanation of 'natural'disasters. *Disasters, development and environment*, 13-30. Retrieved from https://scholar.google.co.in/scholar?hl=en&as_sdt=0%2C5&as_vis=1&q=Vulnerability+analysis+and+the+explanation+of+%27natural%27disasters&btnG=

Cantillo, V. L. (2019). Assessing vulnerability of transportation networks for disaster response operations. *Networks and Spatial Economics*, 243-273. Retrieved from https://pdf.usaid.gov/pdf_docs/PA02127P.pdf

Cheng, C. L. (2005). Long-term prediction of discharges in Manwan Hydropower using adaptive-network-based fuzzy inference systems models. *Springer Proceedings, Part III*. Retrieved from https://www.researchgate.net/profile/Lin-Jianyi/publication/225377949_Long-Term_Prediction_of_Discharges_in_Manwan_Hydropower_Using_Adaptive-Network-Based_Fuzzy_Inference_ Systems_Models/links/02e7e5285c3a09f9f7000000/Long-Term-Prediction-of-Discharges-in-

Chithra, S. N. (2015). Impacts of impervious surfaces on the environment. *International Journal of Engineering Science Invention*, 27-31. Retrieved from https://d1wqtxts1xzle7.cloudfront.net/37942361/E045027031-libre.pdf?1434689794=&response-content-disposition=inline%3B+filename%3DImpacts_of_Impervious_Surfaces_on_the_En.p

df&Expires=1702015162&Signature=fNvvg5jr7xwwVtOLM24MPRihSXFSippFlwnrki2b1-wojB8Xsuf

Choi, J. H.-J.-J. (2012). Combining landslide susceptibility maps obtained from frequency ratio, logistic regression, and artificial neural network models using ASTER images and GIS. *Engineering geology*, 124. doi:10.1016/j.enggeo.2011.09.011

Diaconu, D. C. (2021). An overview of flood risk analysis methods. *Water*, 474. Retrieved from https://www.mdpi.com/2073-4441/13/4/474

Donald A. Wilhite. (2000). Drought as a Natural Hazard:Concepts and Definitions. In NDMC, *Drought* (pp. 3-18). London: National Drought Mitigation Centre. Retrieved from https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1068&context=droughtfacpub

DRONAH. (2016). *Detailed Project Report under Smart City Plan, Jaipur for Amber Development* .

FAO. (1985). *Rainfall and Evapotranspiration*. Retrieved February 16, 2024, from https://www.fao.org/3/r4082e/r4082e05.htm

IMD. (2020). *Urban Flood Management: Drainage and Planning.* Gurgaon: India Water Partnership. Retrieved from https://cwp-india.org/wp-content/uploads/2021/05/REPORT-ON-URBAN-FLOOD-MANAGEMENT-DRAINAGE-AND-PLANNING.pdf

IMD. (2021). *Standard Operation Procedure-Weather Forecasting and Warning.* New Delhi: India Meteorological Department. Retrieved from https://mausam.imd.gov.in/imd_latest/contents/pdf/forecasting_sop.pdf

IMD New Delhi. (2021). *Impact based Forecast for Heavy rainfall.* New Delhi: IMD. Retrieved from https://imdpune.gov.in/imdone/training/training%20notes/Dr%20Jenamani%201st%2030%20AUG%202021.pdf

IMDMC Jaipur. (2020). *Monsoon Report 2020-Rajasthan.* Jaipur. Retrieved from https://mausam.imd.gov.in/jaipur/mcdata/monsoon2020.pdf

IMDMC Jaipur. (2021). *Monsoon Report 2021- Rajasthan.* Jaipur. Retrieved from https://mausam.imd.gov.in/jaipur/mcdata/monsoon2021.pdf

IMDMC Jaipur. (2022). *Rajasthan Monsoon Report 2022.* Jaipur. Retrieved from https://mausam.imd.gov.in/: https://mausam.imd.gov.in/jaipur/mcdata/monsoon2022.pdf

India Meteorological Department. (2020, 2021, 2022). *Rajasthan Monsoon Report.* Jaipur: Meteorological Centre Jaipur. Retrieved from https://mausam.imd.gov.in/jaipur/mcdata/monsoon2022.pdf; https://mausam.imd.gov.in/jaipur/mcdata/monsoon2021.pdf; https://mausam.imd.gov.in/jaipur/mcdata/monsoon2020.pdf

Intellectual Property in India. (2016). *Geographical Indications Journal No.93.* Chennai: Government of India. Retrieved from https://ipindia.gov.in/writereaddata/Portal/IPOJournal/1_416_1/Journal_93.pdf

INTOSAI. (2018). *Managing stormwater systems to reduce the risk of flooding*. Retrieved January 29, 2024, from https://www.environmental-auditing.org/media/116448/auditor-generals-overview-office-of-the-auditor-general-new-zealand.pdf

INTOSAI. (2019). *Government Response to Mitigate the Impact of Flooding*. Retrieved January 29, 2024, from https://www.environmental-auditing.org/media/116555/p03_imp_of_flooding.pdf

INTOSAI. (2020). *https://www.environmental-auditing.org*. Retrieved January 29, 2024, from https://www.environmental-auditing.org/media/zmxdwelw/intosai-wgea-floods-control-measures-final_01062022.pdf

Jaipur World Heritage. (2024). *Jaipur World Heritage*. Retrieved November 17, 2023, from https://jaipurworldheritage.com/overview/: https://jaipurworldheritage.com/

JDA. (2020). *Jaipur walled City*. Retrieved from https://lsg.urban.rajasthan.gov.in: https://lsg.urban.rajasthan.gov.in/content/dam/raj/udh/lsgs/lsg-jaipur/Order/order2019/oct/JHCPR2020.pdf

Juan, N. P. (2022). Review of the application of Artificial Neural Networks in ocean engineering. *Ocean Engineering*, 111947. Retrieved from https://doi.org/10.3390/w14213453

Kar, B. S. (2016). Public participation GIS and participatory GIS in the era of GeoWeb. *The Cartographic Journal*, 296-299. Retrieved from https://discovery.ucl.ac.uk/id/eprint/1536576/1/Haklay_Public%20Participation%20GIS%20and%20Participatory%20GIS%20in%20the%20Era%20of%20GeoWeb%20250117.pdf

Khandelwal, S. (2022). Changing pattern of water supply system in Jaipur metropolitan (Rajasthan, India). *IJAR*, 34-39. Retrieved from https://www.researchgate.net/profile/Shweta-Khandelwal/publication/364198087_Changing_pattern_of_water_supply_system_in_Jaipur_metropolitan_Rajasthan_India/links/633eb07f76e39959d6a37874/Changing-pattern-of-water-supply-system-in-Jaipur-metropolitan-Rajas

Kia MB, P. S. (2011). An artificial neural network model for flood simulation using GIS: Johor River Basin, Malaysia. *Environ Earth Science*, 251–264. doi:10.1007/s12665-011-1504-z

Klijn, F. S. (2008). Towards flood risk management in the EU: State of affairs with examples from various European countries. *International Journal of River Basin Management*, 307-321. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/15715124.2008.9635358

Kron, W. (2005). Flood risk= hazard• values• vulnerability. *Water international*, 58-68. Retrieved from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=9f0c6072b7059c66c31421cbb8b47d429cb1a793

Lyu, H. S. (2018). Flood risk assessment in metro systems of mega-cities using a GIS-based modeling approach. *Science of the Total Environment*, 1012-1025. doi:10.1016/j.scitotenv.2018.01.138

Masood, M. a. (2012). Assessment of flood hazard, vulnerability and risk of mid-eastern Dhaka using DEM and 1D hydrodynamic model. *Natural hazards*, 757-770. doi:10.1007/s11069-011-0060-x

Ministry of Water Resources, River Development and Ganga Rejuvenation. (2018, August 2). *Flood Control Schemes*. Retrieved January 29, 2024, from https://pib.gov.in/Pressreleaseshare.aspx?PRID=1541301

Mit J. Kotecha, G. T. (2023). *GIS-Based Novel Ensemble MCDM-AHP Modeling for Flash Flood Susceptibility Mapping of Luni River Basin, Rajasthan.* Singapore: Springer Nature Singapore. Retrieved from https://www.researchgate.net/profile/Suraj-Singh-8/publication/371919043_GIS-Based_Novel_Ensemble_MCDM-AHP_Modeling_for_Flash_Flood_Susceptibility_Mapping_of_Luni_River_Basin_Rajasthan/links/6500329168ca5847e3d55f8b/GIS-Based-Novel-Ensemble-MCDM-AHP-Model

Mukherjee, S. J. (2013). Evaluation of vertical accuracy of open source Digital Elevation Model (DEM). *International Journal of Applied Earth Observation and Geoinformation*, 205-217. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/S030324341200195X?via%3Dihub

NDMA. (2024). *Floods*. Retrieved November 20, 2023, from https://ndma.gov.in: https://ndma.gov.in/Natural-Hazards/Floods

NDMA Government of India. (n.d.). *Urban Floods*. Retrieved November 17, 2023, from https://ndma.gov.in: https://ndma.gov.in/Natural-Hazards/Urban-Floods

NITI Aayog. (2021). *Report of the Committee Constituted for Formulation of Strategy for Flood Management Works in Entire Country and River Management Activities and Works Related to Border Areas.* New Delhi: National Institution for Transforming India. Retrieved from https://www.niti.gov.in/sites/default/files/2023-03/Report-of-the-Committee-Constituted-for-Formulation-of-Strategy-for-Flood-Management.pdf

OECD. (2016). *Financial Management of Flood Risk.* Paris: OECD Publishing. Retrieved from https://www.oecd.org/daf/fin/insurance/OECD-Financial-Management-of-Flood-Risk.pdf

Ologunorisa, T. a. (2005). Flood risk assessment: a review. *Journal of Applied Sciences and Environmental Management*, 57-63. Retrieved from https://www.bioline.org.br/pdf?ja05010

Osman, S. a. (2023). GIS-based flood risk assessment using multi-criteria decision analysis of Shebelle River Basin in southern Somalia. *SN Applied Sciences*, 134. doi:10.1007/s42452-023-05360-5

Panhalkar, S. S. (2017). Flood risk assessment of Panchganga River (Kolhapur district, Maharashtra) using GIS-based multicriteria decision technique. *Current Science*, 785-793. Retrieved from https://www.currentscience.ac.in/Volumes/112/04/0785.pdf

Pradhan, B. (2010). Landslide susceptibility mapping of a catchment area using frequency ratio, fuzzy logic and multivariate logistic regression approaches. *Journal of the Indian Society of Remote Sensing*, 301-320. doi:10.1007/s12524-010-0020-z

Qin, Y. (2020). Urban flooding mitigation techniques: A systematic review and future studies. *Water*, 3579. doi:10.3390/w12123579

Rabby, Y. I. (2020). Evaluating the effects of digital elevation models in landslide susceptibility mapping in Rangamati District, Bangladesh. *Remote Sensing,*, 2718. Retrieved from https://www.mdpi.com/2072-4292/12/17/2718

Ramesh, V. a. (2022). Urban flood susceptibility zonation mapping using evidential belief function, frequency ratio and fuzzy gamma operator models in GIS: a case study of Greater Mumbai, Maharashtra, India. *Geocarto International*, 581-606. doi:10.1080/10106049.2020.1730448

Saini, S. K. (2016). Flood-risk assessment in urban environment by geospatial approach: a case study of Ambala City, India. *Applied Geomatics*, 163-190. Retrieved from https://d1wqtxts1xzle7.cloudfront.net/58037384/saini2016-libre.pdf?1545329579=&response-content-disposition=inline%3B+filename%3Dsaini2016_pdf.pdf&Expires=1699528486&Signature=adXG~pFpKGLWnj8-bUS4D8eSmYidexuBcrvjqTEYAdu2-qeOL-4GmbKoKiqUFEkzzqF0LmBI7IULtV9

Sansare, D. a. (2020). Natural hazard assessment and mapping using remote sensing and QGIS tools for Mumbai City, India. *Natural Hazards*, 1117-1136. doi:10.1007/s11069-019-03852-5

Scholtes, L. a. (2013). DEM model for soft and hard rocks: role of grain interlocking on strength. *ournal of the Mechanics and Physics of Solids*, 352-369. Retrieved from https://sci-hub.wf/10.1016/j.jmps.2012.10.005

Sebring, P. a. (2000). School leadership and the bottom line in Chicago. *Phi Delta Kappan*, 440-443. Retrieved from https://www.researchgate.net/profile/Penny-Sebring/publication/285515499_School_leadership_and_the_bottom_line_in_Chicago/links/5d5afebb92851c37636bbeb9/School-leadership-and-the-bottom-line-in-Chicago.pdf

Shafapour Tehrany, M. S. (2017). GIS-based spatial prediction of flood prone areas using standalone frequency ratio, logistic regression, weight of evidence and their ensemble techniques. Geomatics. *Natural Hazards and Risk*, 1538-1561. Retrieved from https://www.tandfonline.com/doi/pdf/10.1080/19475705.2017.1362038

Shokri, A. S. (2020). Impacts of flood on health of Iranian population: Infectious diseases with an emphasis on parasitic infections. *Parasite epidemiology and control*, 00144. Retrieved from https://www.sciencedirect.com/science/article/pii/S2405673120300131

Siddayao, G. V. (2014). Analytic hierarchy process (AHP) in spatial modeling for floodplain risk assessment. *International Journal of Machine Learning and Computing*. Retrieved from 10.7763/IJMLC.2014.V4.453

Singh, G. P. (2015). Extreme rainfall events and urban floods in the growing cities of India. *Mausam*, 825-840. Retrieved from https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Extreme+rainfall+events+and+urban+floods+in+the+growing+cities+of+India&btnG=

Sukojo, B. H. (2021). Comparative Analysis of DTM Results with Hydro Enforcement LiDAR Data Method and Interferometric Synthetic Aperture Radar (InSAR) from Radar Satellite Imagery (Case Study of Kebumen Regency). *Conference Series: Earth and Environmental Science*, 012023. Retrieved from https://iopscience.iop.org/article/10.1088/1755-1315/936/1/012023/pdf

Suthakaran, S. J. (2022). Mapping the Flood Risk Exposure Using Open-Source Geospatial Tools and Techniques: A Case of Gampaha Divisional Secretariat Division, Sri Lanka. *Journal of Geoscience and Environment Protection*, 18-31. doi:10.4236/gep.2022.1010002

Tomar, P. S. (2021). GIS-Based Urban Flood Risk Assessment and Management—A Case Study of Delhi National Capital Territory (NCT), India. *Sustainability,*, 12850. doi:10.3390/su132212850

UNFCCC. (n.d.). *Flood hazard mapping*. Retrieved November 29, 2023, from https://www.ctc-n.org: https://www.ctc-n.org/technologies/flood-hazard-mapping

USGS. (n.d.). *What is a digital elevation model (DEM)?* Retrieved from USGS science for changing world: https://www.usgs.gov/faqs/what-digital-elevation-model-dem

Wang, Y. L. (2011). A GIS-based spatial multi-criteria approach for flood risk assessment in the Dongting Lake Region, Hunan, Central China. *Water resources management*, 3465-3484. doi:10.1007/s11269-011-9866-2

Willems, P. A.-N. (2012). Climate change impact assessment on urban rainfall extremes and urban drainage: Methods and shortcomings. *Atmospheric research*, 106-118. doi:10.1016/j.atmosres.2011.04.003

WorldPop. (2023, December 15). *WorldPop Data*. Retrieved from https://www.worldpop.org/: https://www.worldpop.org/

Zhang, D. S. (2020). A GIS-based spatial multi-index model for flood risk assessment in the Yangtze River Basin, China. *Environmental Impact Assessment Review*, 106397. Retrieved from https://eprints.gla.ac.uk/213428/7/213428.pdf