

Assessment of flood dynamics and impacts during the 2022 monsoon-induced flood in eastern Balochistan (Nasirabad) using Google Earth Engine and GIS

Niamat Ullah^{1,2,3,4*} , Shafi Ullah⁵ , Said Qasim⁶ , Muhammad Talha⁷, and Syed Ahmed Shah³ 

¹ State Key Laboratory of Mountain Hazards and Engineering Resilience, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610299, China.

² University of the Chinese Academy of Sciences, Beijing 100049, China.

³ Spatial Decision Support System (SDSS), Lab (NCGSA), Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta 87300, Pakistan.

⁴ Department of Colleges, Higher & Technical Education, Balochistan, Pakistan.

⁵ Department of Computer Engineering, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta 87300, Pakistan.

⁶ Department of Geography and Regional Planning, University of Balochistan, Quetta 87300, Pakistan.

⁷ Institute of Atmospheric Physics, University of Chinese Academy of Sciences, Beijing 100049, China.

*Correspondence: Niamat Ullah niamatullahza@gmail.com

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Abstract: Floods are among the most frequent and destructive natural disasters worldwide, posing significant challenges, particularly in Pakistan. This study uses Sentinel-1 Synthetic Aperture Radar (SAR) data, combined with Geographic Information Systems techniques, to map flood extent in Nasirabad, eastern Balochistan, Pakistan, in relation to the devastating 2022 monsoon floods. Socio-economic data were collected from relevant departments. Pre- and post-flood maps were prepared using Sentinel-1 SAR data in ArcMap 10.8, while Sentinel-2 data were used to produce a land-use and land-cover map of the study area using a support vector machine classifier in Google Earth Engine. The results indicate that the 2022 flooding in Nasirabad was primarily driven by intense upstream rainfall (>500 mm) and inadequate water management infrastructure. The flood extent map revealed that most of the study area faced severe flooding during the 2022 monsoon season. The flood destroyed standing crops and eroded fertile topsoil, displacing thousands of people. Numerous human casualties were reported, and outbreaks of diseases, including gastroenteritis, diarrhea, and malaria, followed the flood. Livestock losses reached 2,310 head, significantly impacting the livelihoods and resilience of rural households. Thirty-two union councils in the district were affected, with a total of 20,830 houses damaged—12,180 partially and 8,650 fully destroyed. Furthermore, 26 community schools were affected, six of which were fully damaged. Infrastructure damage included five bridges and 42 km of roads. These findings reaffirm the need to enhance flood defenses, improve early warning systems, enforce sustainable land-use practices, and design climate-resilient infrastructure to mitigate the impacts of future floods.

1. Introduction

Hydrometeorological disasters are increasing globally (Ginige et al., 2022), particularly in Pakistan (Shah et al., 2025). High rainfall amounts often lead to flooding,

a type of hydrometeorological disaster. Floods are the most common (Jonkman, 2005) and among the most destructive natural disasters (Javadinejad, 2022) worldwide (Munawar et al., 2022; N. Ullah et al., 2024). All types of floods, including flash, urban, and riverine floods, cause extensive damage to agriculture, livestock, buildings, and infrastructure. Floods in the 21st century have become more frequent and more intense due to climate change and anthropogenic activities (Danish Ehtesham et al., 2024). Among anthropogenic activities, human settlement on natural floodplains is the main cause of damage to crops, livestock, and humans. The study by Wang et al. (N. Wang et al., 2023) also confirmed that flood-related damages and losses are primarily attributable to a decrease in the human–river distance.

Floods affect both agricultural and domestic activities, as their impacts can persist long after the event. Pakistan is situated in a hazard-prone region, where extreme weather events contribute to natural disasters, especially floods. The country has a long history of flooding, having experienced recurrent events since its independence in 1947. Over the past seven decades, Pakistan has faced about 29 floods of different magnitudes (Danish Ehtesham et al., 2024), yet it is still not in a position to effectively mitigate their impacts. Pakistan faces both riverine and flash floods. Riverine floods are primarily driven by glacial melt, while flash floods result from sudden rainfall during extreme weather. Among the South Asian nations, Pakistan ranks highest in terms of flood-affected people (Hussain et al., 2023).

Floods in Pakistan pose significant challenges to the health sector (Manzoor et al., 2022; Sarkar, 2022), food security (Muhammad Ahmad, 2022), and infrastructure (Chohan et al., 2024). Notably, over the past two decades, the country has experienced more frequent floods (Manzoor et al., 2022). As many Asian countries, including Pakistan, are developing nations, their vulnerability to floods and other natural disasters is heightened due to limited adaptive and preparedness measures compared with those in the developed world. Under normal conditions, Balochistan receives scant rainfall, approximately 250 mm per year; however, during major flood events, the annual total may increase to around 400 mm due to excessive precipitation. In the 2022 floods, Sindh and Balochistan were severely affected. The 2022 floods in Pakistan are considered the largest in the country's history, triggered by exceptionally heavy rainfall. These events resulted in catastrophic losses: widespread fatality, mass displacement, outbreaks of waterborne diseases, destruction of infrastructure, and damage to standing crops. Almost 1,300 people lost their lives, and 33 million were displaced (Nanditha et al., 2023). The 2022 floods were catastrophic because they affected roughly one-third of Pakistan's land area (Higgs, 2024), severely impacting the provinces of Khyber Pakhtunkhwa, Balochistan, and Sindh (Ambreen et al., 2026; N. Ullah et al., 2026).

Almost all floods in Balochistan have affected the adjoining districts of Jaffarabad and Nasirabad (Danish Ehtesham et al., 2024). Owing to its proximity to Sindh, Nasirabad is prone to flash floods. Flash floods are short-duration, highly destructive events that often occur during the monsoon season due to extreme rainfall and are difficult to predict. The 2022 flash floods affected almost 80% of Jaffarabad district and about 35% of Nasirabad district (Danish Ehtesham et al., 2024). Nasirabad district was severely affected by abnormally high rainfall in July and August 2022. The district is one of Balochistan's districts with high rice productivity. Any external condition that negatively affects plant growth and productivity is considered a source of plant stress (Muhammad et al., 2025). During the July and August floods, estimated crop stress levels in Nasirabad were 26% and 24%, respectively (Yamano et al., 2024). Balochistan faced substantial losses to buildings, cropland, and infrastructure during the 2022 floods, which caused the deaths of 336 people and approximately 400,000 livestock and resulted in 115,822 fully destroyed houses, 125,837 partially destroyed houses, 58 collapsed bridges, and 2221.98 km of affected roads (NDMA, 2022). In Nasirabad, the flash floods not only affected crops and livestock but also severely impacted people and infrastructure.

Geographic information systems (GIS) and remote sensing are both efficient tools for identifying flood zones and reducing flood risk (Diakakis et al., 2019; Kastridis et al.,

2020). These technologies have been effectively used in Pakistan for mapping flood hazard zones and delineating inundated areas (Haq et al., 2012; Uddin et al., 2013). They play a key part in managing flood risk (X. Wang & Xie, 2018). However, research on flood hazard modeling in Nasirabad district remains limited, with existing studies focusing primarily on land-use and land-cover (LULC) change detection (Raza et al., 2023) and direct runoff estimation (Danish Ehtesham et al., 2024). There is a clear gap concerning the development of flood hazard models using GIS and remote sensing for the Nasirabad district of Balochistan. These geospatial techniques will enhance flood hazard models, thereby encouraging more effective resource allocation for flood risk reduction. Thus, the objective of this study is to assess the dynamics and impacts of the 2022 monsoon-induced floods in Nasirabad (eastern Balochistan) using remote sensing data in Google Earth Engine (GEE) and GIS environments.

2. Materials and Methods

2.1. Study area

Nasirabad district was selected as the study area. It is located in east-central Balochistan. This geographical location extends from 67.74° to 68.44° east longitude and 28.20° to 29.09° north latitude (Raza et al., 2023), as shown in Figure 1. The study area was selected due to its heavy rainfall trends (more intense and frequent rainfall) over the past few decades. This pattern is evident in Figure 1E, which shows the trend in mean annual precipitation from 1981 to 2025. Nasirabad is located in the center of Balochistan and comprises four tehsils: Baba Kot, Chattar, Dera Murad Jamali, and Tamboo. It is bordered by Dera Bugti to the east, Jhal Magsi to the west, Bolan to the north, and Jaffarabad to the south. The elevation of the study area ranges from 50 to 170 m above sea level (Hayat et al., 2020). The climate is extremely hot in summer and pleasant in winter. Baloch and Sindhi are the dominant ethnic groups. Nasirabad is considered a fertile region because its soils consist of alluvial deposits formed by recurring floods. Livestock is also reared by the farmers in this area. This district is considered one of the main rice-producing areas of Balochistan. The district covers an area of 5,896 km² (2,273 mi²) (Hayat et al., 2020). The total agricultural area of the district is 215,728 ha (Raza et al., 2023).

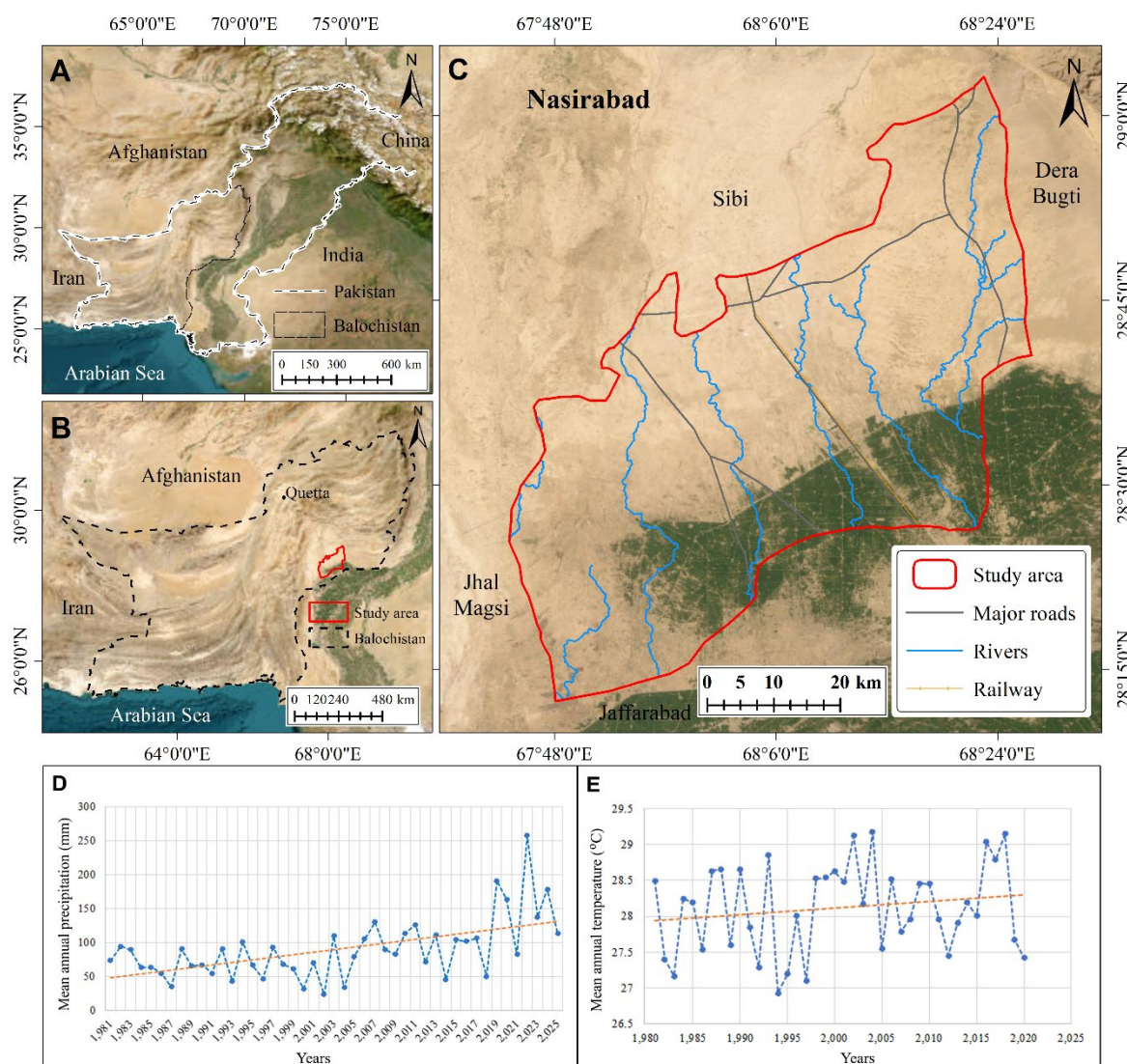


Figure 1. (A) International boundary of Pakistan. (B) Provincial boundary of Balochistan with focus on the study area. (C) Study area map along with major roads, rivers, railway tracks, and elevation (m). (D) Mean annual precipitation in mm. Reprinted from (Hans Hersbach et al., 2023). (E) Mean annual temperature (°C) in the study area. Reprinted data from (Funk et al., 2014)

2.2. Data collection

The study utilized a remotely sensed dataset with a range of temporal and spatial resolutions. These datasets were acquired from multiple satellites and are available to end users at no cost.

2.2.1. Sentinel-1 Synthetic Aperture Radar

Sentinel-1A Level-1 Synthetic Aperture Radar (SAR) ground range detection (GRD) scenes, both pre- and post-flood, were obtained from the European Space Agency's (ESA) Copernicus Programme (<https://scihub.copernicus.eu>) via the Google Earth Engine (GEE) (Belay et al., 2025; Ghouri et al., 2023). In this study, SAR data were used to generate flood inundation maps for 2022. The June composite images represent pre-flood conditions, while the August–September composites represent post-flood conditions. The Sentinel-1 SAR images have a spatial resolution of 10 m and a temporal period of 12 days. Data were acquired using the vertical transmit, horizontal receive (VH) polarization, interferometric wide swath (IW) mode, and descending orbit pass mode (Belay et al., 2025; Ghouri et al., 2023).

2.2.2. Integrated Multi-Satellite Retrievals for the Global Precipitation Measurement Mission Final Run Version 7 precipitation

The most recent product, Integrated Multi-Satellite Retrievals for the Global Precipitation Measurement (GPM) mission (IMERG) Final Run Version 7 (V07) (<https://gpm.nasa.gov/>), offers gridded precipitation data for the whole world on a half-hourly, daily, and monthly basis (Aryal et al., 2025; George J. Huffman et al., 2023). Using estimates from microwave-calibrated infrared (IR) satellites and precipitation gauges, the IMERG Final Run V07 method intercalibrates, combines, and interpolates satellite microwave precipitation estimations (Aryal et al., 2023; Hou et al., 2014; Jain et al., 2022). To measure rainfall over the study area in 2022, the present study utilized the National Aeronautics and Space Administration (NASA)'s IMERG V07 monthly and daily precipitation dataset, which is accessible through GEE. The IMERG monthly collection was filtered for January 1 to December 31, 2022, and the daily rainfall collection for August 1 to September 5, 2022.

2.2.3. Land use and land cover classification and accuracy assessment

The ESA's Copernicus program launched the Sentinel-2 Earth monitoring satellites. The satellites are equipped with a 13-band multispectral imager sensor, with a spectral range of 0.4 to 2.4 μm and a spatial resolution of 10 to 60 m (Table 1). There is a five-day dual-satellite revisit period. The spectral characteristics of various land types were obtained for this study using Sentinel Imaging Level-2A products in GEE, and cloud-shadow pixels were removed using the QA60 band cloud-masking information. This technique filters the pixel values and shades clouds, cirrus, rain, and snow by applying bitwise operations to the QA60 quality band (Chen et al., 2023). For LULC mapping, support vector machines (SVMs) are a popular and powerful machine learning approach. To correctly classify LULC, the SVM classifier technique was used in the present study (Bendeckou et al., 2024; S. Ullah et al., 2025; Wahap & Shafri, 2020).

For LULC classification in the study area, 70% of the samples were used for training the SVM classification algorithm, and 30% were utilized for testing, with a focus on SVM's ability to reduce misclassified pixels (Shaharum et al., 2020). To quantify the classification accuracy of the LULC maps, four measures were used: producer accuracy (PA) (equation 1), user accuracy (UA) (equation 2), overall accuracy (OA), and the Kappa index (κ).

$$PA = \frac{n_{ii}}{n_{+i}} \times 100 \quad (1)$$

where PA is producer accuracy, n_{ii} is the correctly classified samples for class i , and n_{+i} represents the total number of reference samples of class i .

$$UA = \frac{n_{ii}}{n_{i+}} \times 100 \quad (2)$$

where UA is the user accuracy, n_{ii} is the number of correctly classified samples, and n_{i+} is the total number of classified samples in class i .

Equation (3) was used to determine OA, which is the ratio of properly classified pixels to all pixels. Equation (4) represents the Kappa index, which quantifies agreement by chance in the classification process.

$$OA = \frac{\sum_{i=1}^n n_{ii}}{N} \times 100 \quad (3)$$

where OA is the overall accuracy, n_{ii} is the number of pixels for each class that was correctly classified, and N is the total number of pixels.

$$K = \frac{\sum n_{ii} - \sum ef}{N - \sum ef} \times 100 \quad (4)$$

where κ is the kappa index, n_{ii} is the frequency of accurate classifications for each category, ef is the anticipated frequency of accurate classifications by chance, and N is the total number of pixels.

2.2.4. Institutional data

Data on the impacts of the 2022 floods in the study area were acquired from the National Disaster Management Authority (NDMA) and the Provincial Disaster

Management Authority (PDMA). Along with its team, PDMA also mobilizes the multidisciplinary District Assessment Committees, which include staff from revenue, irrigation, agriculture, and other relevant departments. These committees assess the impact of disasters, including crop and household/infrastructure losses. Shapefiles (.shp) of the study area were obtained from the Spatial Decision Support System Lab. Some other images used in this study were obtained from different news sources on social media.

Table 1. Detailed description of the datasets used in the present study

Dataset	Variable	Acquisition period	Spatial resolution	Temporal resolution	References
Sentinel-1 SAR	Flood inundation	Aug–Sep 2022	10 m	12 days	(Belay et al., 2025)
IMERG Final Run V07	Precipitation	Jan–Dec 2022	~0.1° (~10 km)	Daily/Monthly	(George J. Huffman et al., 2023)
Sentinel-2	Land cover	June 2022	10 m	5 days	(S. Ullah et al., 2025)

2.3. Data pre-processing and analysis

Pre-processing was performed on the collected data. Geometric and radiometric distortions, thermal noise, and speckle are common sources of error that affect Sentinel-1 SAR images (Belay et al., 2025; Filipponi, 2019). Therefore, before the data can be used to map flood inundation, this noise must be removed through preprocessing. On the GEE platform, the following pre-processing steps were applied: (i) The orbit's information is updated via orbit file rectification. (ii) Border noise reduction removes erroneous data, such as low-intensity noise, from the scene's borders. (iii) In SAR data contexts with multi-swath acquisitions, additive noise, such as discontinuities between sub-swaths, is eliminated by thermal noise reduction. (iv) Based on sensor calibration parameters, digital pixel values are converted to calibrated SAR backscatter coefficients (σ^0) via radiometric calibration. (v) Terrain correction is applied to remove geometric distortion in SAR images.

Sentinel-1 Level-1 GRD images that had already undergone automated pre-processing procedures were utilized for the present research study (Belay et al., 2025). The Sentinel-1 SAR images were downloaded and exported to a GIS for pre- and post-flood mapping of the study area. The IMERG data collection was filtered to select monthly and daily products and spatially clipped to the study area. The clipped data were exported as a raster file from GEE to the ArcMap 10.8 (Esri, US) domain for further analysis. This study employs different machine learning approaches to perform LULC classification using Sentinel-2 Level-1C data with 10 m resolution. Orthorectified images with minimal cloud cover were used as the primary input, and the cloud mask method on the GEE platform was employed to exclude contaminated pixels from all accessible images caused by cloudy circumstances (Loukika et al., 2021). Furthermore, data collected from different institutions were incorporated into the flood impact assessment, and summary statistics, figures, and maps were produced using Microsoft Excel, CorelDRAW X7, and GIS software. The detailed methodological framework is shown in Figure 2.

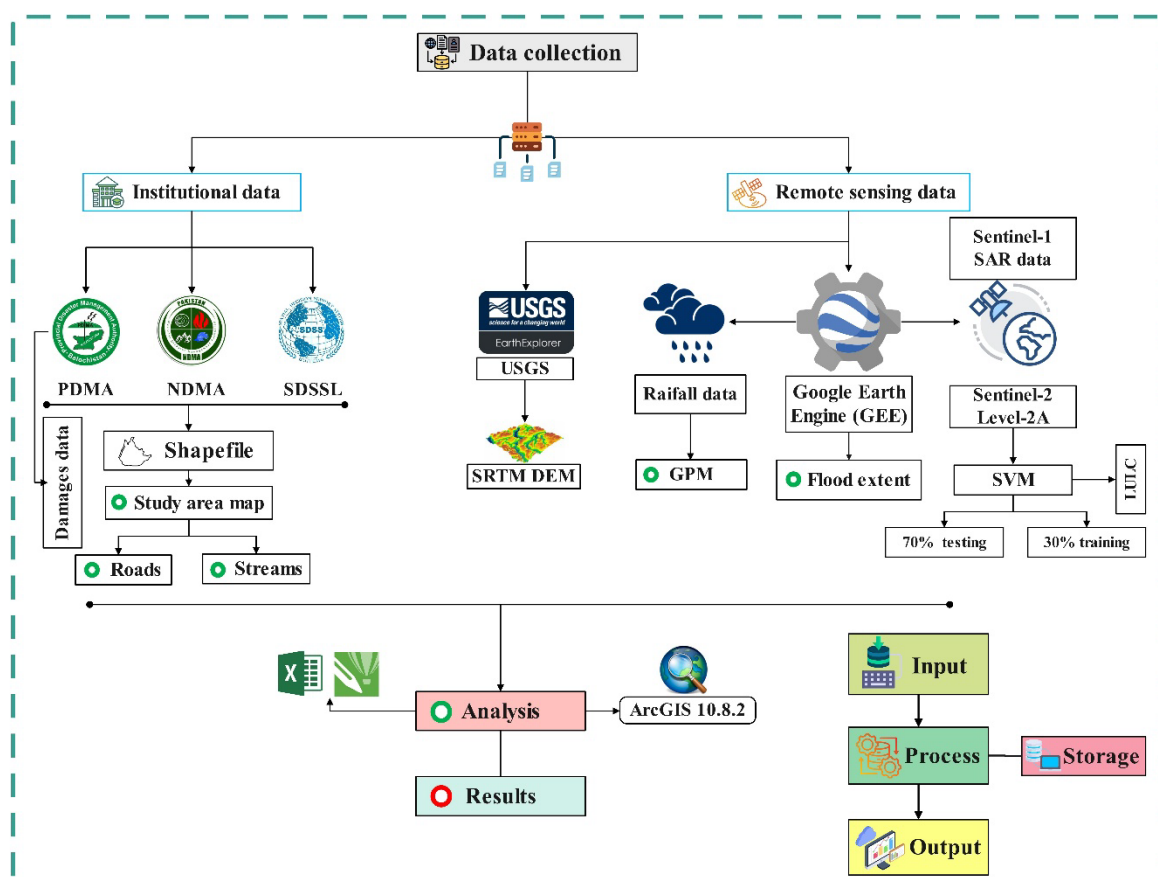


Figure 2. The detailed methodological framework in the present study. Abbreviations: GPM: Global Precipitation Measurement; LULC: Land use and land cover; NDMA: National Disaster Management Authority; PDMA: Provincial Disaster Management Authority; SAR: Synthetic Aperture Radar; SDSSL: Spatial Decision Support System Lab; SRTM DEM; SVM: Support vector machine; USGS.

3. Results

3.1. Climate and flood risk profile

Nasirabad lies in an arid to semi-arid climatic zone, with an average annual rainfall of 150–200 mm. However, Balochistan experienced rainfall 590% above average in August 2022, triggering catastrophic flooding as the Nari and Bolan rivers breached their embankments. Unlike Sindh’s subtropical monsoon dynamics, Nasirabad’s flooding is driven by intense, localized rainfall in upstream catchments and by inadequate water-management infrastructure. Historical neglect of floodplain zoning and embankment maintenance has amplified risks, with recurring floods displacing communities and eroding livelihoods.

3.2. Rainfall distribution

The amount and seasonal distribution of rainfall play a crucial role in determining flood impacts and associated risks. There is a direct relationship between rainfall intensity and flood vulnerability: higher precipitation increases flood risk, while lower precipitation decreases it. IMERG is frequently utilized in hydrological and climatological research (Pradhan et al., 2022; Sapountzis et al., 2021), due to its combined observation technique, high temporal resolution, and relatively fine spatial resolution of $\sim 0.1^\circ$ (~ 10 km). The collected IMERG images were filtered to specify monthly and daily products, and clipped spatially to the study region for dates between January 1, 2022, and December 31, 2022 (monthly) (Figure 3A) and between August 1, 2022, and September 5, 2022 (daily) (Figure 3B).

In Nasirabad, the 2022 rainfall data revealed significant variations in precipitation patterns, which directly influenced local water levels and exacerbated surface water

flooding. Peak rainfall events in 2022 occurred in July and August, intensifying flooding by saturating soils and overwhelming drainage systems.

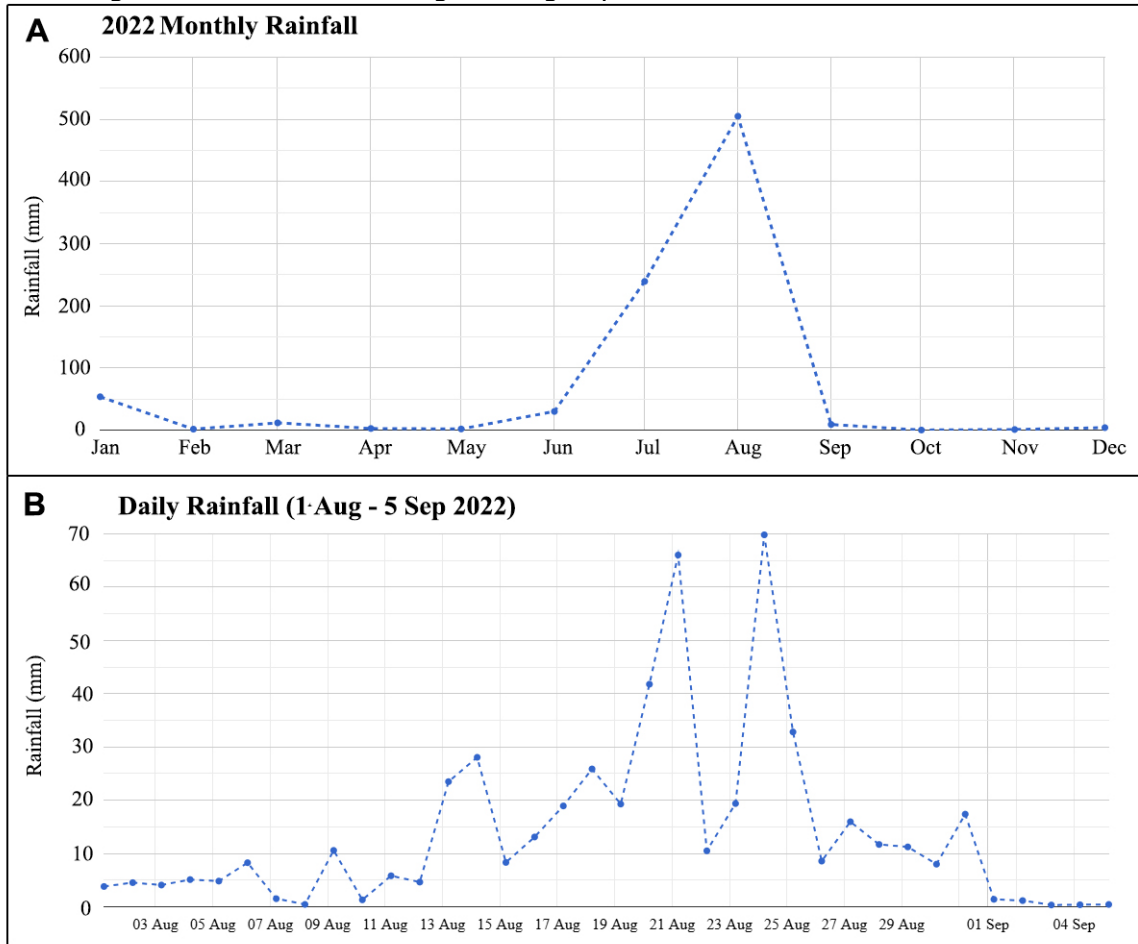


Figure 3. Patterns of (A) monthly and (B) daily rainfall during the 2022 floods in the study area.

3.3. Flood inundation

The GEE environment was used to identify flood inundation using Sentinel-1 SAR data. This process included several steps, such as pre-processing, change detection, data collection, image filtering, flood extent export, and mapping. Pre-flood imagery was acquired between 1–30 June 2022 (Figure 4A), whereas post-flood imagery was obtained between 20 August and 5 September 5 (Figure 4B), and the flood extent map (Figure 4C) was prepared using ArcMap 10.8 domain. The flood extent map revealed that most areas of the district faced severe flooding in the 2022 monsoon season.

The 2022 monsoon floods significantly impacted Nasirabad District, Balochistan, causing widespread inundation of agricultural and built-up areas. Sentinel-1 SAR satellite assessment showed that the highest flood extent in Nasirabad during the flood reached about 931.2 km². The extensive flooding hindered agricultural activities, destroyed infrastructure, and affected the livelihoods of local communities. These findings highlight the significance of GIS and remote sensing for precise flood mapping and disaster management planning.

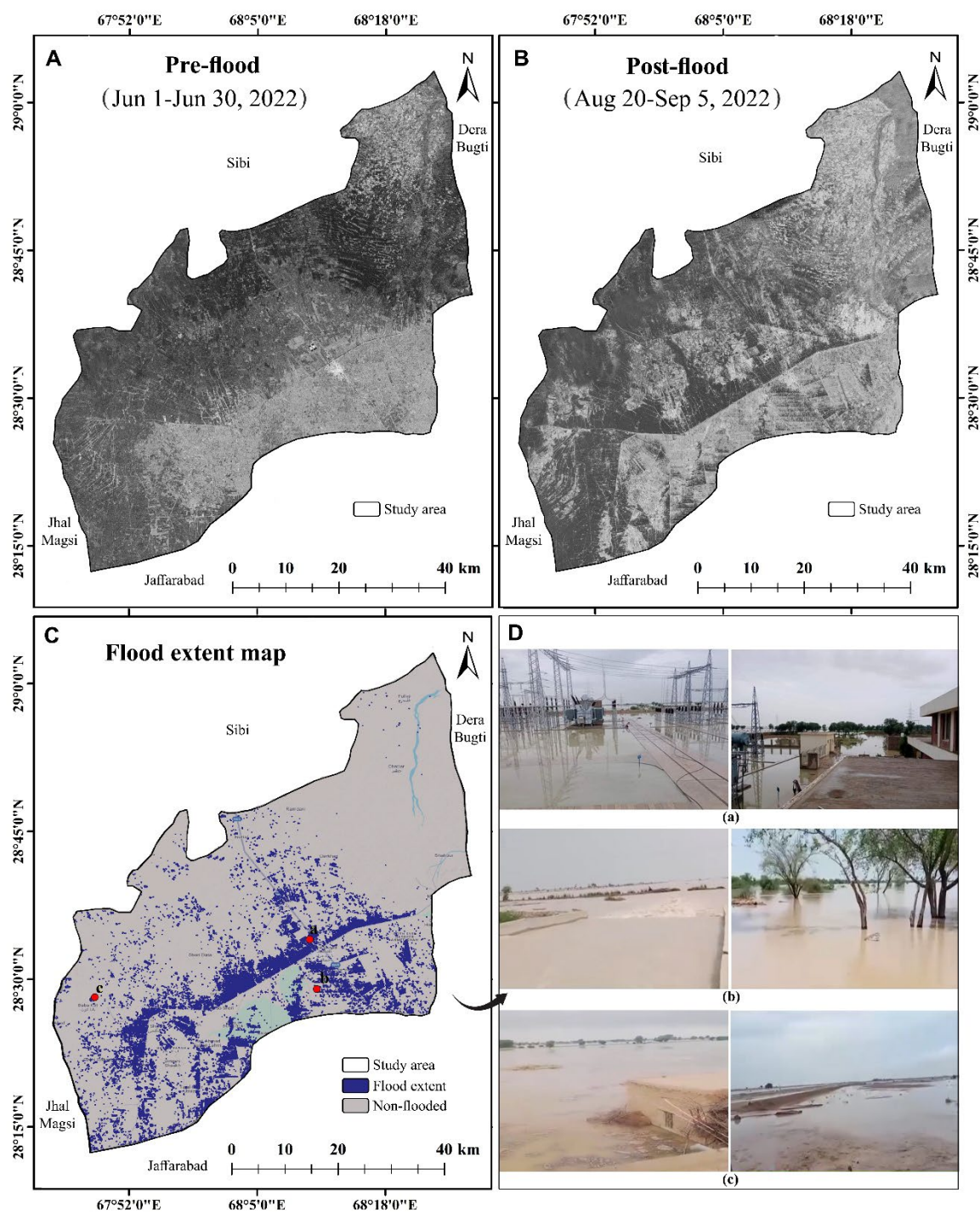


Figure 4. Inundation map of the study area. (A) Pre-flood map, (B) Post-flood maps, (C) Flood extent map of the study area, with most affected area points in red color, and panel (D) depicts the flood situation in the study area.

3.4. Land use and land cover

Land use and land cover are critical determinants of flood behaviour. Areas dominated by forests and agricultural land generally exhibit higher infiltration rates, meaning a significant portion of rainfall is absorbed into the soil, reducing surface runoff and consequently lowering flood risk. Vegetation plays a vital role in intercepting rainfall and promoting water infiltration, thereby acting as a natural buffer against flooding. In contrast, urbanized zones with extensive impervious surfaces, such as roads, buildings, pavements, and concrete structures, greatly diminish the ground's ability to absorb water. During heavy rainfall, these surfaces prevent water from infiltrating the soil, resulting in rapid accumulation of surface runoff. This excess water swiftly flows into

drainage systems and watercourses, often overwhelming them and causing urban flooding. Bare land or sparsely vegetated areas have moderate infiltration capacity but can contribute to surface runoff if rainfall intensity exceeds the land's absorption capacity. The rapid expansion of urban areas and deforestation in Nasirabad have intensified flood vulnerability, emphasizing the need for sustainable land management practices, vegetation preservation, and controlled urban development to mitigate flood impacts (Ghouri et al., 2023). The SVM technique in GEE was used to extract LULC classes for 2022. Using GEE, the entire LULC analysis process encompassed data collection, pre-processing, image classification, and visualization. The current study area was divided into four LULC classes: vegetation, water bodies, built-up area, and barren land, as shown in Figure 5.

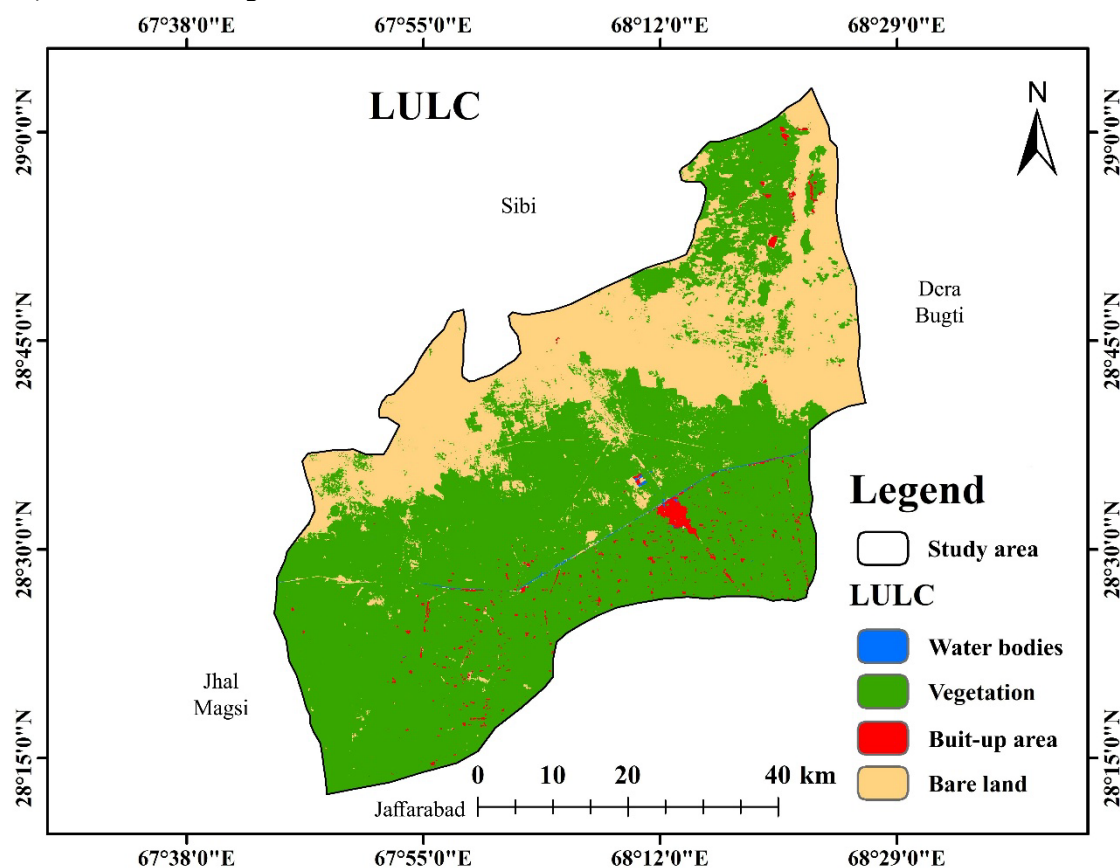


Figure 5. Land use and land cover (LULC) of the Nasirabad district.

3.4.1. LULC classification accuracy assessment

The accuracy of the produced LULC classification was assessed using an independent validation dataset including 30% of the reference samples. OA, PA, UA, and the Kappa coefficient (κ) were computed. The SVM classifier had an OA of 95.8% and a K of 0.94, signifying excellent agreement between the classified map and the reference data. The findings illustrate the robustness of the classification and confirm that the resulting LULC map is appropriate for further analysis of flood dynamics. Vegetation demonstrated greater classification performance due to its unique spectral characteristics, achieving a PA of 97.2% and a UA of 96.5%. Water bodies attained high classification accuracy (PA = 98.0%, UA = 97.0%) due to their distinctive spectral response. The PA and UA of each LULC class are shown in Table 2.

Table 2. Accuracy assessment of the Sentinel-2 LULC map for Nasirabad, Balochistan.

LULC class	PA (%)	UA (%)
Water bodies	98.0	97.0
Vegetation	97.2	96.5
Built-up area	91.0	90.2
Bare land	94.3	95.1

3.5. Flood dynamics

The produced flood inundation map derived from Sentinel-1 SAR data was overlaid onto the classified LULC map of the study area in ArcMap 10.8. environment. This multi-temporal technique facilitated the evaluation of variations in flood extent across the main land cover classes and provided insights into flood dynamics. The flood extent is mostly absorbed in the southern and central areas of the study area, where the produced LULC map indicates a high proportion of the vegetation class. Slightly inundated areas are present on bare land, while a small portion of built-up areas is submerged, as shown in Figure 6. The extensive flooding of vegetated areas indicates the significant vulnerability of agricultural fields to the 2022 monsoon floods, resulting in considerable crop losses and disruptions to rural life. On the other hand, flooding in urban areas was concentrated in communities along floodplains, where water accumulated due to flat terrain and inadequate drainage systems.

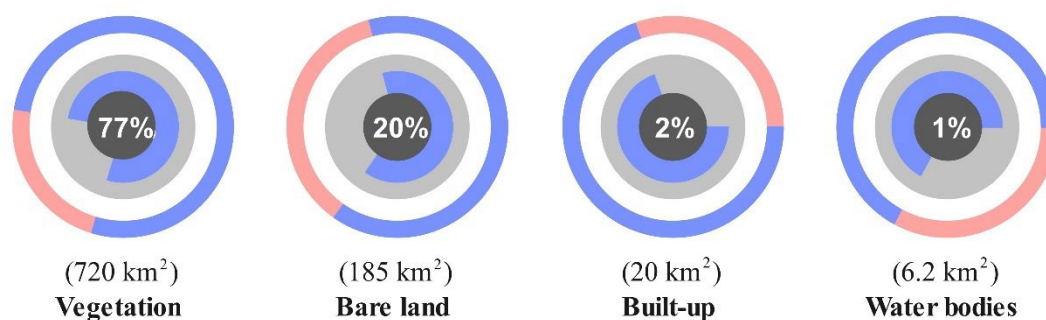


Figure 6. Inundated area and percentages of LULC classes of the study area during the 2022 flood.

3.6. Impacts of the 2022 floods in the study area

Pakistan is among the nations most susceptible to the widespread, multisectoral effects of climate change. In 2022, the country saw catastrophic floods brought on by unprecedented monsoon rainfall, which damaged infrastructure and left millions of people homeless. The eastern districts, including Nasirabad in Balochistan, were among the most severely affected by the 2022 floods. The majority of these districts are rural, with the local economy primarily based on agriculture. In addition to destroying standing crops, the floodwaters carried away the fertile topsoil, which is essential for future crop growth. Nasirabad was also severely impacted. Thousands of individuals were displaced by the floods, and many of them took up residence in temporary shelters with no access to essential services. Relief operations were hindered by the damage to infrastructure, including roads, bridges, and medical facilities. This prevented remote villages from getting aid on time.

3.6.1. Impacts on living beings

Nasirabad district was one of the most severely flood-affected areas, facing a considerable number of casualties and livestock losses. The livestock losses were mostly due to flooding, disease, and a shortage of available fodder. According to the PDMA, 2,310 livestock were lost during the 2022 floods in the study area (PDMA, 2022) (Figure 7). The loss of animals has a significant impact on the livelihood and resilience of rural households. The large number of cattle deaths placed a significant burden on regional food systems, restricting access to animal-based nutrition, such as meat and milk, in the study area. Following the flooding, outbreaks of diseases such as gastroenteritis, diarrhea, and malaria occurred in Nasirabad.



Figure 7. Impacts of the 2022 floods on (A) humans and (B) livestock in the study area.

3.6.2. Impacts on infrastructure

Houses and infrastructure in Balochistan suffered significant damage from the 2022 monsoon floods. The floods also damaged several facilities in the Nasirabad district, including homes, roads, and bridges. Thirty-two union councils were affected in the district (DTM-IOM, 2022). In total, 20,830 houses were damaged, including 12,180 partially damaged, and 8,650 fully damaged houses, mainly in areas of Dera Murad Jamali, Baba Kot, and Tumboo (Figure 8). Five bridges and 42 km of roads were also damaged in Nasirabad (Figure 9) (PDMA, 2022). According to the Balochistan Education Foundation, 26 community schools were affected, including six fully damaged schools (Balochistan Education Foundation, 2022).



Figure 8. Impacts of the 2022 floods on physical infrastructure in the study area.



Figure 9. 2022 flood damage in the study area.

PD- Partially Damaged, FD- Fully Damaged; Source: PDMA

3.7. Causes of floods in the study area

High-speed floodwaters can exceed design loads by exerting hydrodynamic pressures on foundations, walls, abutments, and other structures (Nadal et al., 2010). In 2022, the monsoon rainfall in Balochistan reached 500–600% of climatological averages at this time (Nanditha et al., 2023), causing severe floods in the province, particularly in the study area. Nasirabad is located downstream of the mountainous catchment regions on the province's level plains. These lowlands are especially susceptible to floods as water comes down from the mountains, particularly during periods of heavy rainfall and when rivers overflow. In 2022, floodwater from the Moula River near Nasirabad caused cracks

in the Pat Feeder canal (The Nation, 2022). Another cause of the floods in the study area was the failure of the infrastructure, such as poor construction of the houses, roads, and limited drainage capacity; for example, floodwater entered the 220 kV Dera Murad Jamali grid station, resulting in power outages that worsened the situation in the study area, as shown in Figure 4D.

4. Discussion

This research used Sentinel-1 SAR data to identify damage in Nasirabad district, Balochistan, during the 2022 floods. The findings indicate that this region is highly vulnerable to flooding, which has been disastrous for local inhabitants and has severely impacted the country's agrarian economy. Sentinel-1 proved to be a reliable source for flood mapping in Nasirabad, effectively highlighting the inundated area during the 2022 floods. This technique was also used in a study conducted in the Sindh province, Pakistan (Ghouri et al., 2023). The frequency of floods in Balochistan has increased, driven by factors including climate change, inadequate disaster management, and a lack of awareness. Consequently, floods pose great threats to livestock, human beings, and infrastructure (Shahzad et al., 2021).

In a larger climatological context, Blöschl et al. (Blöschl et al., 2019) demonstrated that, depending on changes in precipitation, evapotranspiration, and snowmelt processes, climate change has caused both increases and decreases in river flood magnitudes throughout Europe, with significant regional variation (e.g., increases in northwest Europe, declines in southern and eastern regions). Their findings highlight that flood responses to climate change are mediated through several interacting variables (e.g., soil moisture, seasonal changes, and evaporation) rather than rainfall alone, and they warn against assuming a uniform rising trend in flooding everywhere. To improve the interpretation of flood dynamics in monsoon-driven environments, it is essential to exercise caution when drawing broad conclusions and to consider a variety of mediating factors beyond precipitation. Under the tagline "Everything Flows" (Montanari et al., 2013), the Panta Rhei project portrays hydrological systems as essentially dynamic and closely related to social transformation. The project contends that hydrology should be viewed as a co-evolving human–water interface, in which feedbacks between hydrological processes (runoff, infiltration, and flood regimes) and society (population growth, land use, and infrastructure) are crucial, rather than as a static system that merely responds to climatic forcing. The co-evolutionary approach encourages consideration of how human activities, such as the expansion of settlements, the operation of canals and feeders, and changes in land cover, may have changed the system's sensitivity to monsoon inputs.

The 2022 floods reached exceptionally high levels in Nasirabad. The findings of this study underscore the importance of flood mapping for policymakers, decision-making authorities, agricultural departments, and the government. Additionally, these results provide vital information for disaster management and preparedness for affected areas in Balochistan, including Nasirabad (Glavan et al., 2020). 70 percent of villages were submerged by the 2022 floods. Infrastructure across this district was also severely affected, in addition to the loss of life and injuries. Therefore, mitigating flood impacts in any shape demands proactive disaster preparedness. Although the objectives of this study were limited, the impacts of floods on mental health and waterborne disease should be addressed in future studies. Furthermore, modeling high-frequency floods in Nasirabad is an important area for future studies (Luu et al., 2023).

4.1. Policy implications and future recommendations

The frequency of floods in Balochistan is increasing significantly due to rapid climate change, creating greater uncertainty and risk. The escalating threat underscores the urgent need for timely mitigation measures. The findings of this study offer insights for effective flood risk management in the study area and other similar regions. Based on these results, the following recommendations are proposed for future action:

- Develop an advanced and effective local disaster management department with the capacity to mitigate the negative impacts of floods in Nasirabad.

- Ensure strong and timely coordination between provincial and federal disaster authorities.
- Construct flood shelters in Nasirabad to accommodate displaced communities.
- Promote awareness of flood risks and preparedness among local communities to mitigate disastrous impacts.
- Regularly update flood maps and implement proactive flood risk management measures to reduce the severity and complexity of flood impacts in Nasirabad.
- Prioritize land use planning by policymakers, including restricting construction in flood-vulnerable areas, to reduce loss of life and economic losses.
- Validate IMERG estimates against ground station measurements, as previous research has demonstrated that IMERG rainfall estimates frequently underestimate peak intensities during heavy rainfall, especially in convective or complicated terrain (Koutsoyiannis et al., 2023; Li et al., 2023; Mohammed et al., 2025).

4.2. Limitations

This research possesses several limitations. Sentinel-1 SAR data may underestimate flooding under dense vegetation. Institutional damage data may contain reporting inaccuracies, and IMERG Final V07 precipitation predictions were not verified against local rain-gauge measurements due to insufficient ground data.

5. Conclusion

Nasirabad lies in an arid to semi-arid climatic zone, with an average annual rainfall of 150–200 mm. However, Balochistan experienced 590% above-average rainfall in August 2022, triggering catastrophic flooding. The purpose of this study was to identify inundated areas in Nasirabad district and to highlight the damage caused by the 2022 floods. To achieve this, flood inundation mapping was conducted, and secondary data from various sources, including PDMA and NDMA, were utilized to support the analysis. The 2022 floods in Nasirabad district clearly illustrate the high susceptibility of dry and semi-arid areas to climate-related disasters, highlighting the urgent need for effective flood risk management. Sentinel-1 SAR remote sensing data and GIS technology highlighted that most villages in the district were inundated, revealing severe socio-economic impacts, including loss of lives, livestock, housing, and key infrastructure. Approximately 2,310 livestock were lost during the 2022 floods in the study area, significantly affecting rural households' livelihoods, resilience, and food security by reducing the availability of animal-based products such as meat and milk. Thirty-two union councils were affected, and 20,830 houses were damaged, including 12,180 partially damaged and 8,650 fully damaged houses. Additionally, five bridges and 42 km of roads were damaged in Nasirabad. Thousands of individuals were displaced and forced to reside in temporary shelters with no access to essential services.

The results illustrate systemic weaknesses, such as flat terrain, poor drainage infrastructure, and settlements encroaching on natural floodplains, that collectively increased the magnitude and altered the spatial distribution of flood events. These findings reaffirm the need to enhance flood defenses, improve early warning systems, enforce sustainable land-use practices, and develop climate-resilient infrastructure to mitigate future flooding. Furthermore, the study demonstrates the significant potential of remote sensing and GIS as affordable, reliable tools for real-time monitoring, disaster assessment, and evidence-based decision-making, and their adaptability to resource-limited environments. In the future, an integrated strategy combining technological innovation, community outreach, and policy changes will be critical to strengthening resilience to increasing climate variability and promoting the security and well-being of vulnerable communities in Nasirabad and similar flood-prone regions. It will be necessary to develop adaptive capacity through planning and sustainable management to minimize the socio-economic and environmental costs of future flood events and to promote sustainable development in the context of ongoing climate change. Thus, the integration of Sentinel-1 SAR, Google Earth Engine, and GIS establishes a rapid and cost-free framework for flood monitoring in data-scarce areas.

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Author contributions

Niamat Ullah conceived the study and wrote the article. Shafi Ullah and Said Qasim supervised the study. Muhammad Talha contributed to the methodology, and Syed Ahmed Shah contributed during the revision.

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Conflict of interest

The authors declare no conflict of interest.

Availability of data

Data and materials for the present study are available upon request from the corresponding author.

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