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Urban Flood Risk Mapping and Vulnerability Assessment in Gwadar: A GIS-based Approach

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Abstract

Urban flooding has become an increasingly severe global challenge, particularly affecting cities in developing nations where rapid and unregulated urbanization, deficient infrastructure, and climate change converge to create compounded risks. Gwadar, a strategic coastal city in Balochistan, Pakistan, exemplifies this vulnerability. Positioned at the heart of the China-Pakistan Economic Corridor (CPEC), the city is undergoing rapid transformation yet remains critically unprepared for recurring flood events. This research employs a mixed-methods design integrating Geographic Information Systems (GIS)-based spatial analysis with a survey-based socio-economic vulnerability assessment. High-resolution topographic data, land use classification, are combined with structured community surveys (N=286) to develop a comprehensive flood risk profile for Gwadar. A composite Urban Flood Risk Perception Index (UFRPI) is constructed using four dimensions: exposure, sensitivity, adaptive capacity, and mitigation trust, reflecting how residents perceive and experience flood vulnerability. GIS-based flood risk maps reveal severe exposure in low-lying coastal areas including Faqeer Colony, Nayabad, Main Bazaar, and Old Town. Meanwhile, socio-economic indicators such as income, housing quality, and education level show a strong correlation with perceived risk, particularly in informal settlements. The UFRPI scores confirm significant concern over institutional readiness and resilience capacity.

***Keywords*:** urban flooding, flood risk assessment, GIS spatial analysis, socio-economic vulnerability, coastal urban resilience

Introduction

Urban flooding has become a serious concern in developing world because of unregulated urban development and inadequate infrastructures

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(Dharmarathne et al., 2024). Flood risks are also being worsened by climate change which increases rainfall amounts and causes rise in sea-level. Rapid increase in urbanization causes a form of impermeability on the surface which impedes natural water collection and drainage, further increasing flood hazards (Poussin et al., 2014).

The urban population of the world has grown significantly over the years with now 4.4 billion people living in the urban centers as compared to 746 Million people in 1950, a trend that is expected to grow, which makes urban centers more vulnerable to different hazards such as flooding (Hallegatte et al., 2017). Floods are the highest ranked natural hazard that is experienced globally and they result in high loss of life and destruction of property. For example, 2010 Pakistan floods, affected more than 20 million people by displacing them and destroying their infrastructure and agriculture economy (Atta-Ur-Rahman & Shaw, 2015). This brings into attention the devastating effects of floods especially in developing countries with weak urban planning and disaster managers (Anand et al., 2020).

Gwadar in the south west coast of the Pakistan has great importance and has strategic significance because of the China-Pakistan Economic Corridor (CPEC). With Gwadar experiencing sharp growth in its population and infrastructure, the city is also exposed to a rising risk of floods which is likely to compromise the urban growth and financial opportunities of the city. The city has also witnessed other flooding instances in the past, with the worst happening in February 2023, on which the flood waters submerged vast areas of the city, destroying considerable amounts of infrastructure and forcing tens of thousands of people out of their homes (National Disaster Management Authority [NDMA], 2023). The susceptibility of Gwadar to urban floods can be attributed mainly to lack of drainage infrastructure, unregulated urban sprawling growth and substandard urban flood risk analysis tools.

GIS (Geographical Information Systems) in flood risk mapping has been used successfully in most cities in the world as a flood risk management tool wherein urban planners determine flood prone locations, identify the inherent faults and propose mitigation measures (Tomar et al., 2024). Nevertheless, such studies have not been done in Gwadar. Lack of GIS flood risk mapping in the city implies that areas prone to flooding in the city are never identified hence not preparing the city against future floods. Thus, this research will be filling this gap by offering GIS based flood risk assessment model of Gwadar incorporated with physical, socio-economic, and environmental data to improve flood risk management and advance city planning-related activities.

Literature Review

Urban flooding has emerged as a critical challenge in rapidly urbanizing coastal cities due to climate change, sea-level rise, uncontrolled land-use change, and inadequate drainage infrastructure (Sebastian et al., 2022; Kundzewicz et al., 2023). The expansion of impervious surfaces and disruption of natural drainage systems significantly increase the frequency and intensity of urban floods, particularly in developing countries (Alshammari et al., 2023).

Geographic Information Systems (GIS) are generally accepted as the key to the effective assessment of the risks of urban floods due to the ability to combine topographic, hydrological, meteorological, and land-use data into spatial decision-making systems (Chen et al., 2025; Khosravi et al., 2019). GIS can greatly enhance the precision of flood inundation mapping when used with hydrological and hydraulic models, including HEC-RAS, HEC-HMS, and SWAT (Islam et al., 2019). Additional methods such as Analytical Hierarchy Process (AHP) and DEMATEL, are Multi-Criteria Decision Analysis (MCDA) procedures that enhance flood susceptibility mapping by prioritizing dominant flood-inducing factors (Gupta & Dixit, 2022; Ullah et al., 2024).

It has been demonstrated in the literature that the vulnerability to floods is not only limited to physical exposure but is also socio-economically sensitive and adaptively challenged (Ibrahim et al., 2024; Waseem et al., 2023). The poorest housing quality, poor access to infrastructure, and weak institutional support always characterize informal settlements and low-income groups as the most vulnerable ones (Duy et al., 2018; Kundzewicz et al., 2023). Participatory flood management and citizen-science approaches have been shown to improve risk awareness, data collection, and community resilience (Barua & van Ast, 2007; Mohuya et al., 2025).

Flood prediction and early warning have been enhanced by the recent developments in remote sensing, machine learning, and climate modelling based on scenarios (Gilandeh et al., 2020; Tomar et al., 2024; Wang et al., 2023). However, there is a research gap in the literature in the context of emerging secondary coastal cities, where the lack of hydro-meteorological data and the rapid process of urbanization require specific GIS-based flood risk assessment models (Barlaas et al., 2017; Budiyono et al., 2015). This study addresses this gap by applying an integrated spatial flood risk assessment tailored to Gwadar's environmental and socio-economic conditions.

Methodology

The research methodology applied for this study was use of GIS-driven approach and a mixed-method research design. The survey data obtained through questionnaire was linked to spatial data analysis to determine the risk, susceptibility and socio-economic impact of the flooding to the urban population of Gwadar, Balochistan, Pakistan.

Research Design

In order to reflect the complexity of urban flooding in Gwadar, the present study used a convergent parallel mixed-methods design. Such design enables both quantitative and qualitative data to be collected and analyzed simultaneously, thus facilitating triangulations and a more detailed perception of a flood risk. The study design is built on the premises of two major pillars:

Spatial Hazard Mapping (Analysis by the use of GIS)

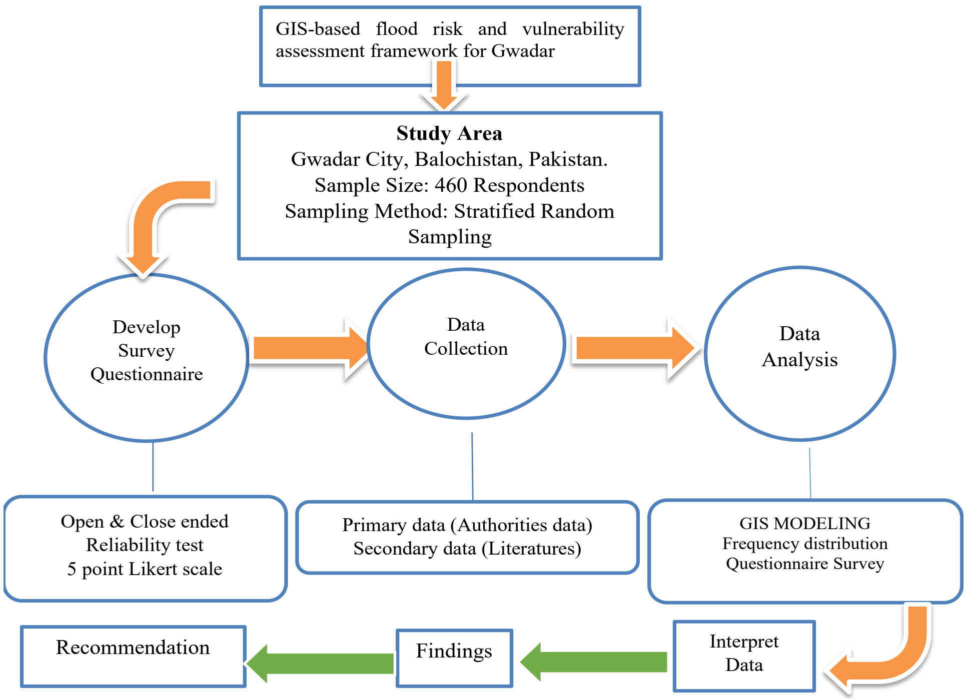
This item relied on multi-layer spatial analysis in which various tools to include ArcGIS 10.8, QGIS 3.22, and ERDAS Imagine were used to provide flood hazard maps. There had been discussion of spatial analysis of digital elevation models (DEMs), land use/land cover (LULC) data and infrastructure maps to locate low-lying and high risk areas. The outcome flood hazard classification allows visualizing the hydrological vulnerabilities on the neighborhood level.

Survey of Household

Flood risk dimension through perceived vulnerability, risk perception, adaptive capacity and mitigation strategies. The residents were interviewed from neighborhoods in Gwadar by means of a structured questionnaire. In the survey, socio-economic vulnerability, household preparedness, past flood exposure and confidence in the institutional response to flooding were assessed. Urban Flood Risk Perception Index (UFRPI) was calculated with the use of the data provided in this survey and the cross-section between physical risk and human vulnerability.

Figure 1

Research Design



Stratified random sampling method is used to select the sample to allow a variety of social-economic groups and geographical locations within Gwadar. Referring to the fact that Gwadar population is about 138,438 according to Cochran Sampling Formula the sample size of the survey was calculated. The necessary value of sample size is determined as:

Under Yamane formula (1967) sample size:

$$n = \frac{N}{1+N\,(e)\,2}$$

Where:

n= size of sample

N = size of the population (138438)

e = margin of error (0.06 or 6%)

$$n = \frac{138000}{1+138000(0.06)2} = \frac{138000}{1+497} = \frac{138000}{498} = 277$$

Final number of samples: 277 respondent

Stratified purposive approach was taken as follows:

- Most effected neighborhood
- Moderate effected neighborhood
- Low effected neighborhood

The proportionate allocation of this sample to these areas is done in regards with population density and risk of floods

Spatial Data Collection and Analysis Procedure

The following primary and secondary geospatial datasets were used:

Table 1
Spatial Source

Dataset	Source	Spatial Resolution	Purpose
SRTM DEM (Shuttle Radar Topography Mission)	USGS Earth Explorer	30 Meteres	Elevation & slope analysis for flood flow modeling
Sentinel-2 Imagery (Multispectral)	Copernicus Open Access Hub	10-20 meters	Land use/land cover (LULC) classification
Administrative Boundary of Gwadar	Pakistan Bureau Statistics	Vector Shapefile	Urban boundary delineation
Drainage & river network data	Derived from DEM using hydrological tools	Raster/Vector	Stream network and watershed mapping

Questionnaire-Based Data Collection Procedure Data Collection Method

The questionnaire was designed around the Urban Flood Risk Perception Index (UFRPI) framework and divided into five thematic sections:

Section A – Socio-demographic profile (gender, age, income, housing type, area of residence)

Section B – Flood exposure (frequency, severity, location-based impact)

Section C – Sensitivity/vulnerability (housing condition, household dependents, health, income loss)

Section D – Adaptive capacity (access to early warning, evacuation plans, insurance, recovery speed)

Section E – Risk perception and community mitigation (trust in authorities, willingness to contribute, awareness of plans)

Responses were collected using a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) to compute quantitative indicators for UFRPI.

Results

Key findings from Socio-Demographic Analysis

The socio-economic background of survey respondents in Gwadar City shows disparities and dependencies factors that increase flood vulnerability. For example, marked gender disparity was recorded, where men make up 81.5% of participants and women only 18.5%, suggesting absence of inclusive disaster management. Survey data show a correlation between educational attainment and floods readiness. Respondents with secondary or higher education reported greater awareness of flood warnings, evacuation routes, and mitigation measures, while those with no or primary education, representing over 40% of the sample, largely relied on informal information channels or past experience rather than official alerts. This suggests that low literacy level among respondents limits the community's capacity to understand early warning systems, hazard maps, and disaster response mechanisms reinforcing findings from similar urban flood studies in South Asia (Duy et al., 2018).

Quality and security of housing came out to be another big determinant of vulnerability. Although 51.8 per cent of the respondents had declared that they lived in pucca (permanent) houses, 48.2 per cent lived in either kutcha (temporary) or semi-pucca houses, structures that are structurally more likely to seep, collapse, and break in cases where floods occur. These poor forms of housing have been found to be concentrated in informal or low income settlements that lack or have non-functional municipal drainage and protection infrastructure risking the residence to frequent damages and evictions. Besides, house ownership dynamics indicate that the percentage of homestead owners is 75.1, and therefore, the houses have a possibility of structural upgrades on a localized and community-based. The other portion, though, especially the 15.3 percent who rent and 9.6 percent who live in state owned housing solely depend on government based safeguarding systems. This highlights the relevance of the mitigation strategies that complement property owners and consider not only policy instruments to protect tenants and renters, who are frequent inhabitants of the most vulnerable areas of the urban fringe.

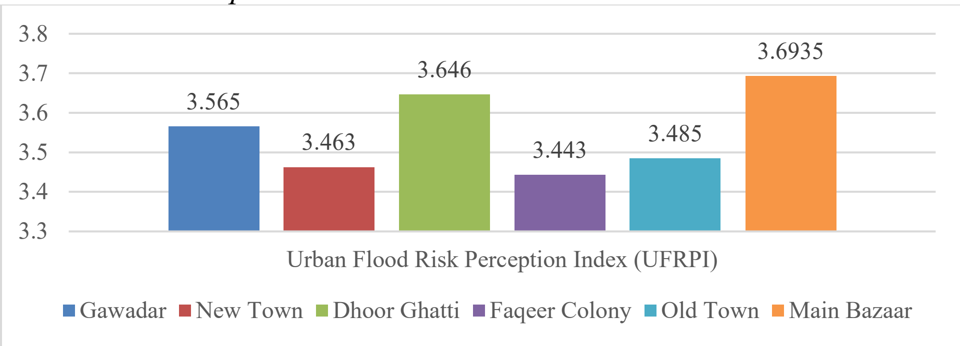
Spatial concentration of the respondents in the neighborhoods that are prone to flood also adds to the urban flood vulnerability. Most of the respondents stated to have lived in Old Town, Mir Lal Baksh Ward (Main Bazar), New Town, Ghatti Dhoor, and Faqeer Colony, where flood disaster hotspots were also indicated in the GIS-based flood risk and susceptibility map. Such communities have high density, inadequate elevation, low access to blocked natural drainage and lack of storm-water pipes that makes them highly vulnerable to flooding and water logging in the event of monsoons. It was interesting to note that, according to 153 of the respondents (or more than 53 percent of the sample), Old Town was the most flood-affected assessable area, followed by Faqeer Colony (78), Main Bazar (67), Dhoor Ghatti (65), and Nayabad/Shambey Ismail Ward (62). This is a clear similarity between perceived and mapped vulnerability which creates an opportunity to go out there and co design interventions with the already knowledgeable residents who are already exposed to this risk.

To conclude, socio-economic background of the Gwadar population indicates a risk-exposed urban environment with vulnerabilities compounded by low rates of education, poor constructions quality, unbalanced gender representation, and a high population density living in flood-sensitive communities. These results highlight that the proper flood resilience in Gwadar has to shift away from the top-down approach to bringing flood mitigation infrastructure and include social components like education, housing opportunities equity, gender inclusion, and local involvement to establish a truly resilient coastal city.

Urban Flood Risk Perception Index (UFRPI)

Figure 2

UFRPI Index Graph

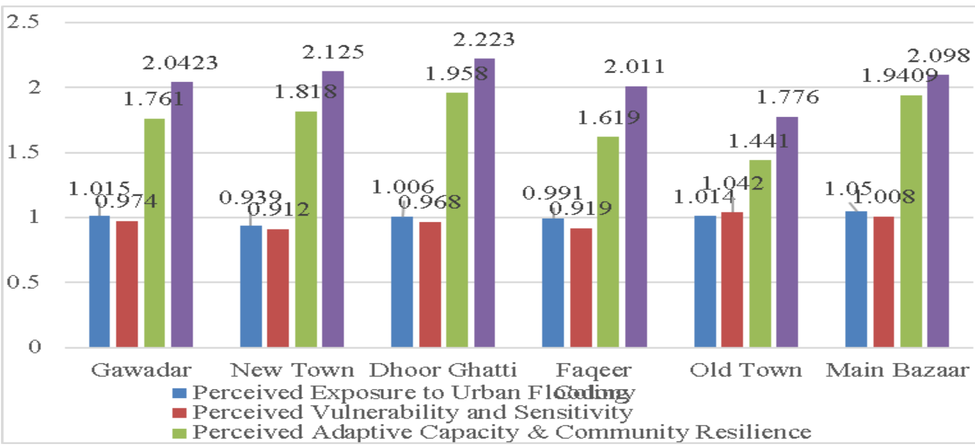


The UFRPI combines several dimensions of perception exposure, sensitivity, adaptive capacity and trust in mitigation strategies to a cumulative score. The lower the score, the less the flood risk perception. It indicates that the highest level of flood risk is perceived by residents of Main Bazaar and Dhoor Ghatti, considering that there is a high density of streams here and the ground elevation is low. Interestingly, Faqeer Colony and New Town had comparatively lower risk perception in view of their spatial vulnerability and this may indicate a perception-reality gap that may be a result of lack of sufficient awareness or normalization of the risk.

Dimensional Analysis of Flood Risk Perception in Gwadar

Figure 3

Perceived Flood Risk Dimension



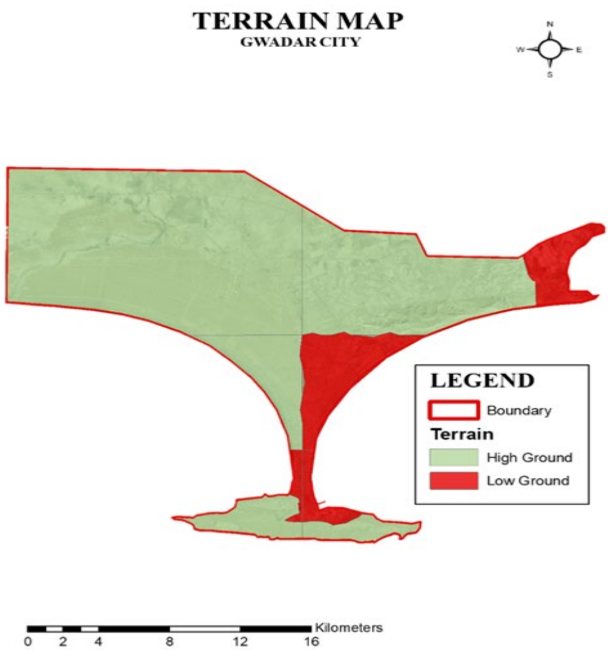
To have a detailed perspective of the perception and experience of urban flood risk by various regions in Gwadar, the UFRPI was broken into four analytical dimensions. All these dimensions provide a different view of social construction of flood risk and interaction of the community with flooding hazard. The findings show clear spatial differences in how communities in Gwadar perceive urban flood risk. Main Bazaar and Old Town reported the highest perceived exposure and vulnerability, reflecting their low-lying locations, obstructed natural drainage, dense urban form, and fragile housing conditions, while Dhoor Ghatti and Faqeer Colony showed moderate exposure linked to poor municipal drainage. New Town had a relatively lower exposure and vulnerability, which could be due to low estimations of risk and not safety. Dhoor Ghatti and Main Bazaar were found to have the highest perceived capacity to cope with flood based on their high social networks and experience of floods in the past, and the Old Town and Faqeer Colony were found to have moderate capacity in terms of capacity based on limited material resources. The resilience of New Town was not as strong as it could have been, and it indicated a lack of governance and organization with the planned development. Government mitigation and response were also positively perceived at the highest in the Dhoor Ghatti, Main Bazaar, Faqeer Colony, and New Town, but low in Old Town. In total, the findings indicate the disproportionate risk awareness, dependence on social instead of institutional resilience, and the necessity of risk-specific communication, detailed planning, and building trustful relations between the government and communities, particularly the most susceptible areas.

Spatial GIS-Based Analysis of Flood Risk and vulnerability Assessment

Terrain-Based Flood Vulnerability Interpretation

The Terrain Map of Gwadar City as seen in the above illustration is fundamental in the comprehension of the natural inclinations of City Gwadar when it comes to urban flooding. This map describes the terrain in two groups of broad terrain type: High Ground (green), and Low Ground (red) based on elevation data, which was retrieved through Digital elevation models (DEM). The map shows that low Ground area in Gwadar covers a considerable part of the southern peninsula area inclusive of the Old Town, Shambey Ismail Ward, and Nayabad. These regions are either at or slightly above the sea level and greatly prone to flooding, particularly during high tide and cyclonic phenomenon. The major corridor passing vertically through the city also shows a large strip of low elevation that serves as a natural stormwater drainage. Uncontrolled development of the urban area has however blocked this channel to a large extent making the potential drainage channel into a flood prone area. Contrastingly, the northwestern and northern areas of Gwadar together with portions of the New Town extension is located at High Ground. Such areas are less prone to flooding naturally hence do their contribution to the increase of run-off volume to the lower areas.

Figure 4
Terrain Map

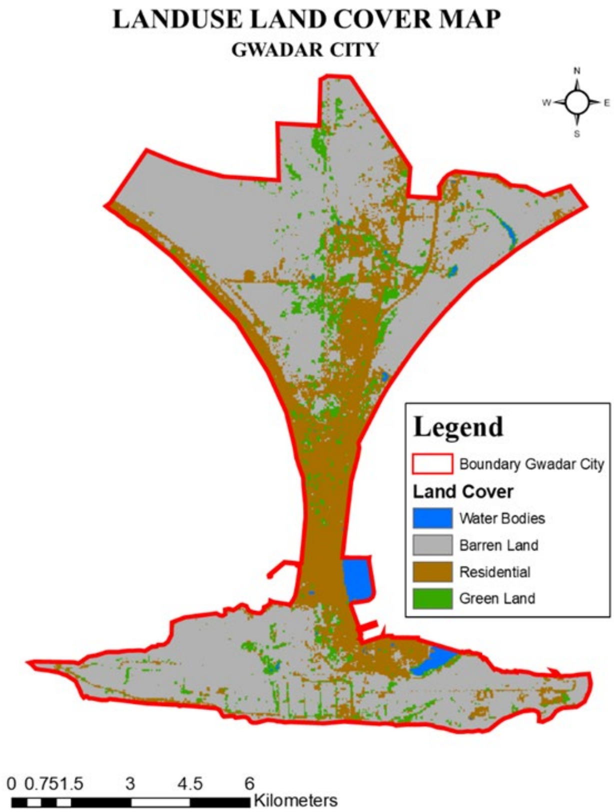


The areas of low terrain that were identified as the most flood-prone in community questionnaire and GIS-based zonation are located directly on the red zones. This confirms their perceptions of the risks facing them with topographic data physically. When monsoon happens, all the water of the places situated on the highlands (green zones) reaches at a great speed into these red zones. This causes the water to pool too fast when there is no functional drainage and retention system resulting in destruction of facilities and causing loss of life.

Land Use and Land Cover (LULC) Analysis

Figure 5

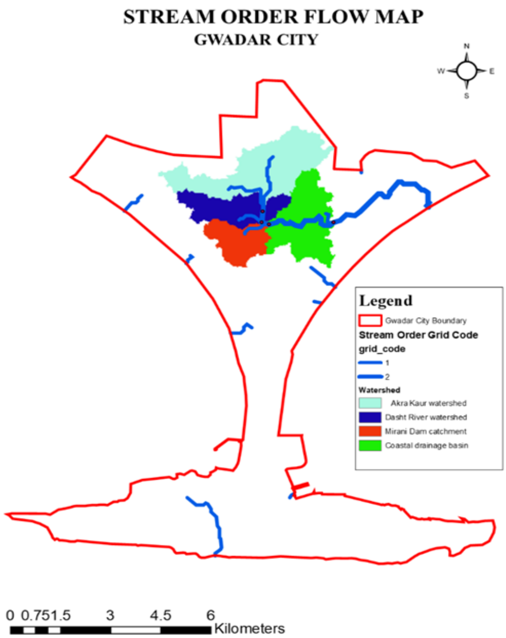
LULC Map



Land Use and Land Cover (LULC) Map of Gwadar City offers substantial information about spatial distribution of human settlement, vegetation, natural water bodies and barren land- each of these variables are important in helping to define the extent of flood exposure and adaptive capacity in the city. It can be seen that residential zones are heavily concentrated in the southern and central belt of Gwadar. A lot of these settlements are involved in lower elevation areas which make these communities vulnerable to floods. There are inhabited areas that are located very close to the observed water bodies (blue), especially in the southern neck of Gwadar. The exposure to tidal flooding and regression of the water table contributes to the worsening of floods in these zones. The city has lost natural green belts and water courses due to urbanization which makes the land less permeable, raises the volume of runoffs and cuts off natural flow routes. The northwest and the southern ends of the peninsula are inhabited by vast tracts of barren land (gray). Though they are not inhabited or developed now, the fast process of urbanization can turn them into developed ones, without adding robust infrastructure, whereas an area with damaged infrastructure will be vulnerable in the future.

Stream Order Flow Map

Figure 6
Stream Order Map

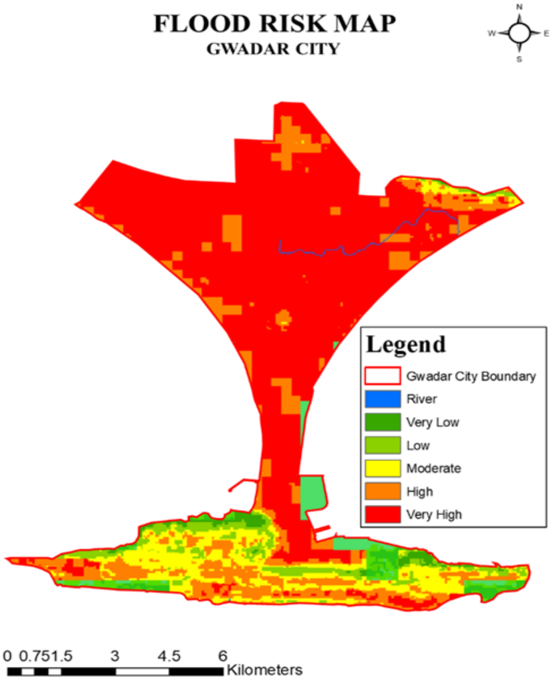


The Important and secondary directions of natural drainage of the Gwadar City are marked in Stream Order Flow Map and the watersheds of the streams. It aids in the evaluation of the motion of surface water at the time of rainstorms.

Primary streams (Order 2) are found around the central and eastern areas which play the significant role as natural medium of the runoff. Secondary flows (Order 1) flow outward and enter the residential districts particularly towards the northwest and core city, comprising Faqeer Colony, Main Bazaar and New Town. The current sets of stream paths conform to areas prone to floods that are found in the terrain and on the questionnaire records. The invasion of natural streams as a result of uncontrolled urban development has resulted in the loss of stream capacity, a factor that has increased dangers of flash floods. Its drainage basin, the coastal basin that flows to the Arabian Sea is congested and poorly maintained and this leads to the higher retention of floods within lowland urban areas.

Flood Risk Map

Figure 7
Flood Risk Map



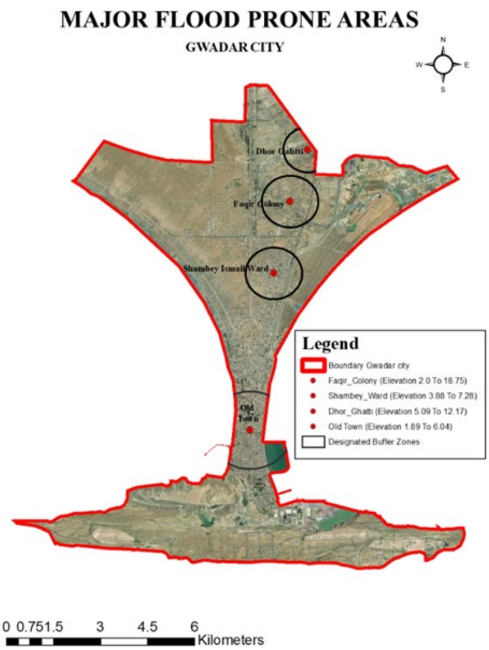
The Gwadar City Flood Risk Map was composed to give a compounded graphical implication of the exposure of flood vulnerability in the geomorphology of the city. It is a synthesis layer within the GIS which is produced by overlapping of several layers such as terrain, land use, hydrological flow and socio-economic exposure layers.

The largest risk category includes central and northern Gwadar such as close low settlements as Old Town, Nayabad, Shambey Ismail and coastal belts. Such regions are poorly drained, highly exposed and have low adaptation capacity. The zones of High Risk (orange), located near red zones, are also greatly vulnerable to floods because of secondary stream intersections, concentration of urban run-off and concentration of informal housing. The areas marked in yellow & green are moderate and low risk zones, respectively, largely situated in the south western and north western fringes where the terrain is relatively higher than the central, the population density is low and the land is either bare or green. The zone with very low risk are marked in yellow located in north Gwadar that the region can be well developed safely as long as guided. This spatial output is used for creating a flood-sensitive urban planning guideline to define future settings of critical infrastructures, planning retention basins and early warning systems.

High-Risk Flood Zones: Delineation of Critical Localities in Gwadar

Figure 8

Major Flood-Prone Areas Map

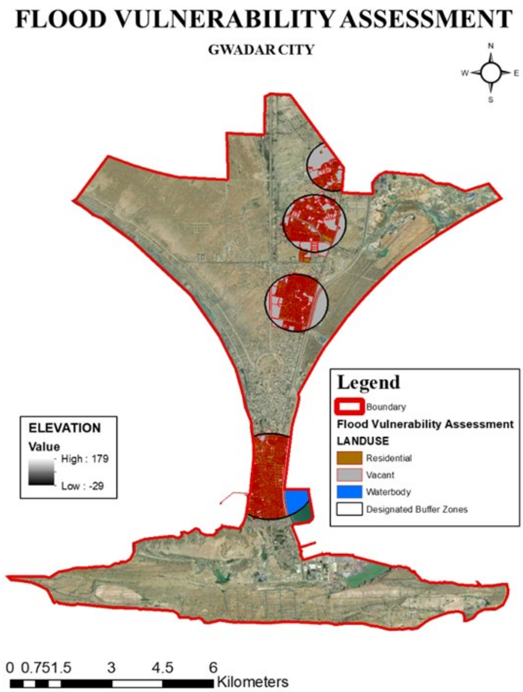


The map above spatially pinpoints the most vulnerable residential zones based on composite flood risk assessment, topography, and hydrological flow dynamics. All these areas fall within low-lying terrain corridors and disrupted drainage zones, making them susceptible to stormwater stagnation and runoff accumulation. Old Town represents the lowest elevation zone, directly abutting the coast, and is surrounded by impermeable surfaces with no structured drainage marking it as most flood vulnerable. Faqeer Colony and Dhoor Ghaati lie in areas where natural stream channels converge with densely populated settlements, increasing exposure to flash floods. Shambey Ward sits on moderately low terrain, but is constrained by both inadequate outflow paths and poor-quality housing, enhancing its risk.

Flood Vulnerability Assessment: Spatial Land-Use and Exposure Mapping

Figure 9

Flood Vulnerability Assessment Map



On the Flood Vulnerability Assessment Map, the blocks of deep red indicate a high-density residential occupation in the buffer Zones, which increases vulnerability. The empty land in buffer zones can be used in future relocation or other flood-reduction facilities like retention basins and emergency shelters. Limited water bodies are situated near flood-prone settlements, and this body of water should be checked in case of overflow. The Old Town coastal corridor is the most vulnerable urban zone based on all indicators. This map links the environmental exposure and the location of human settlements, offering a real-world depiction of vulnerability concentration, in Gwadar.

In general, there is an alignment between GIS-derived flood risk maps and the UFRPI findings especially in districts like Old Town and Dhoor Ghatti which show both substantial modeled exposure and high perceived risk. However, discrepancies emerge in certain locations such as New Town and Faqeer Colony, where perceived risk of flood is lower than spatially modeled exposure. These differences might indicate risk normalization, lack of awareness of hazards or the limited recent severe flood incidents, indicating the inherent limitations of relying solely on perception-based indicators. On the other hand, the lack of fine-scale hydrological and drainage data, which may underestimate localized flood dynamics, and the resolution of the DEM limit the results of spatial modeling. Acknowledging these uncertainties emphasizes how crucial it is to combine social and physical datasets for a more thorough evaluation of urban flood risk.

Discussion

The results of the spatial and socio-economic assessments in this research offer a detailed overview of urban flood hazards in Gwadar. The GIS evaluation identified vulnerable areas, namely Old Town, Faqeer Colony, Shambey Ismail Ward and Dhoor Ghatti, that lie in low-lying floodplain, with limited elevation buffers. These neighborhoods are historically underserved, lack proper drainage systems, and often feature densely packed, unplanned housing structures.

Additionally, the socio-economic analysis indicates that the primary contributors to flood risk in Gwadar are housing quality, elevation of the location and educational level of the residents. Among these factors, housing quality and location have the strongest impact since families living in kutcha and semi-pucca buildings in low-altitude areas, like Old Town, Faqeer Colony and Dhoor Ghatti regularly experience greater exposure, frequent damage and slower recovery. Education level acts as a secondary but indicator of vulnerability, defining the residents' ability to interpret early warnings, access to information, and engagement with local institutes to follow mitigation mechanisms. Gender imbalance further compounds vulnerability by limiting the visibility of women's specific risks, although its impact is mediated through cultural and mobility constraints rather than direct exposure.

Results from the Urban Flood Risk Perception Index (UFRPI) and its dimensions—exposure, sensitivity, adaptive capacity, and mitigation perception—further substantiated the GIS-based vulnerability hotspots. Households in Old Town and Dhoor Ghatti reported high exposure and low adaptive capacity, with many respondents acknowledging frequent flooding, minimal structural resilience, and lack of access to flood mitigation resources. These realities reflect a critical mismatch between formal urban planning efforts and lived experiences on the ground.

The recurring floods, most recently in February 2023, have displaced thousands, inundated homes, and destroyed livelihoods. Although Gwadar's Master Plan 2019 (Gwadar Development Authority [GDA], 2019) articulates long-term resilience objectives, its effectiveness is undermined by weak implementation mechanisms and insufficient integration of flood risk mapping into zoning decisions. Furthermore, limited coordination between planning authorities and municipal service agencies constrains timely and effective interventions. Flood mitigation measures remain largely infrastructure-centric and centralized, with minimal incorporation of local risk knowledge or neighborhood-scale adaptation strategies. As a result, informal and low-income settlements, despite being the most exposed, remain outside the scope of effective intervention.

Conflict of Interest

The authors of the manuscript have no financial or non-financial conflict of interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

Data associated with this study will be provided by the corresponding author upon reasonable request.

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