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Extent and socio-economic impacts assessment of 2022 floods in Nushki, Pakistan, using Google Earth Engine, RS, and GIS

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ABSTRACT

Background: Floods are among the most common and devastating natural disasters worldwide, causing significant damage to people, the economy, and the environment. It is a recurrent phenomenon in Pakistan. The Nushki District of Balochistan also faced severe consequences from the 2022 floods.

Objectives: This study utilizes remote sensing (RS) data within a geographic information system (GIS) environment to map flooded areas and comprehensively analyze the socio-economic impacts of the 2022 floods in one of the most severely affected areas in Balochistan.

Methodology: The flood extent of the study area was prepared using Synthetic Aperture Radar (SAR) remote sensing data of Sentinel-1 through Google Earth Engine. Furthermore, the flood damage data is obtained from the National Disaster Management Authority (NDMA) and the Provincial Disaster Management Authority (PDMA). The collected data was further processed and analyzed using different software. ArcMap 10.8, Microsoft Excel, and CorelDRAW were used to generate maps, tables, and graphs for the present study area.

Results: The findings of the study reveal that floods in 2022 occurred more in the Daak sub-tehsil of the Nushki District. At least one male and three children lost their lives, and several injuries were recorded. A total of 2,229 livestock were lost in the study area because of the severe floods of 2022. The destroyed houses in the study area numbered 4,763, including 2,597 that were fully destroyed and 2,166 that were partially destroyed. The impacts in the agriculture sector include the loss of more than 2,783 acres of agricultural land in the study area.

Conclusion: The flood disasters in Balochistan have highlighted the region's inhabitants and infrastructure's extreme vulnerability. Future flood risk management in Balochistan must place a high priority on resilient rebuilding, enhanced early-warning systems, and sustainable drainage infrastructure. The generated flood extent maps will help policymakers to make preparedness plans and actions in the study area.

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1. INTRODUCTION

Floods are defined as when water runs through streams, submerging areas that are not usually affected by water flows (Intergovernmental Panel on Climate Change (IPCC), 2012). Flood is a transdisciplinary natural hazard whose dimensions and reach are expanded by its correlation with climate change (Waseem & Rana, 2023). The main causes of flood disasters are changing climatic conditions, such as drastic shifts in precipitation patterns and rising temperatures (Hussain et al., 2023). Floods are one of the most common natural disasters in the world, which cause significant damage to the economy, society, and human life (Allafta & Opp, 2021; N. Ullah et al., 2024). Floods have been worse during the last thirty years as a result of human activities, which alter the climate and land usage (Chakrabortty et al., 2022; Detrembleur et al., 2015). Some of the human activities that cause floods include land degradation, construction of properties in the flood zone, and deforestation in the upstream catchments.

Over 30% of natural disasters that happened in the past century were caused by floods, which also resulted in significant devastation, the loss of many lives, and the destruction of valuable property. Developing nations are more exposed to these threats because they lack the adaptive ability and proper infrastructure to handle natural disasters like floods (Shah et al., 2019). Although natural and climatic changes are primarily responsible for the rise in flood hazards in developing countries, human activities such as river encroachment also intensify the severity of flood impacts(Shah et al., 2017). Alongside conditions of drainage basins, including pre-existing river water levels, snow and ice cover, soil character and status (moisture content, permeability, and its vertical distribution), urbanization rate, and the existence of dikes, dams, and reservoirs, can also have an impact on floods (Kundzewicz et al., 2014). In large river basins, intense and long-lasting rainfall is the primary cause of river (fluvial) floods, while high-elevation regions are prone to snowmelt floods, which are sometimes boosted by ice jams or rain. Floods have a greater impact on South Asian countries during the summer monsoon season (June to September), due to more lives and livelihoods are being destroyed than in any other region on the globe (Almazroui et al., 2020). More than 1 billion people in South Asia have been impacted by floods in the last 20 years (EM-DAT, https://public.emdat.be/data). Extreme floods are becoming more common in South Asian countries (Mirza, 2011) and are expected to become more frequent in the future due to climate change (Alfieri et al., 2017; Hirabayashi et al., 2013). The South Asian Subcontinent, which includes the Great Himalaya Glaciers, is still at high risk. Although the rainy season is currently the main cause of flooding in the region, the region is still permanently threatened by the presence of glaciers and rising average temperatures. With a 40% occurrence rate, floods are the most frequent natural disaster in the area (Chaudhry Qamar Uz Zaman, 2017). In addition, 9.6 million people in Bangladesh, India, and Nepal have been impacted by urban floods brought on by poor solid waste management and a decline in urban vegetation, with 6.8 million of them affected in India alone.

1.1. Background and theoretical foundations of research

In Pakistan, millions of people are impacted by floods each year, making the country one of the most vulnerable to floods. Nearly 30 million people reside in regions that are completely vulnerable to flooding (Shakeel Mahmood et al., 2024). In Pakistan, floods are a common occurrence that are mostly caused by high precipitation during the summer monsoon season and infrequently by tropical cyclones. Pakistan has been severely affected by floods since its creation, i.e., the 1950s, 1960s, 1970s, 1980s, 1990s, and most recently in 2022. The 2010 flood was the worst in the country's history. It affected 45 of the 135 districts and lasted for six months, with an estimated damage of 9.7 billion US dollars, 20 million displaced people, 1.1 million destroyed homes, and 432 damaged healthcare facilities (Alderman et al., 2012). The flood of 2022 impacted over 30 million people in different areas of Pakistan, and it also caused significant damage valued at nearly 30 billion US dollars (Khan et al., 2021). One of Pakistan's major provinces, Balochistan, also suffered significant damage to houses, agriculture, and infrastructure during the 2022 flood. In August 2022, Balochistan province received 590% more rainfall since 1961 (Pakistan Meteorological Department (PMD), 2022). According to the National Disaster Management Authority (NDMA), in Balochistan, the flood of 2022 killed 336 people, injured 187 others, and destroyed 400,000 livestock in 32 of the 34 districts, and there have been damages to 2,222 kilometers of roads, 214,659 homes, and 58 bridges (National Disaster Management Authority (NDMA), 2022). A resilient infrastructure, better urban design, and proper disaster management strategies are needed to reduce the danger of floods in Balochistan. There is a lack of research work regarding the extent of the 2002 floods and their socio-economic impacts in the Nushki district of Balochistan based on Remote Sensing and Geographic Information System (GIS). By utilizing remote sensing (RS) data in a geographic information system (GIS) environment, this study is an attempt to map flooded areas and comprehensively analyze the socio-economic impacts of the 2022 floods in one of the most severely affected districts (Nushki) of Balochistan. This study provides unique data and insightful findings that are helpful for disaster management and future policy-making in Balochistan.

2. METHODOLOGY

2.1. Study Area

Balochistan is the largest province in terms of area, with an extent of 347,190 km2, or 43.6% of Pakistan's total land area (S. Ullah, Ullah, Tariq, Panezai, et al., 2025). Quetta is the provincial capital and most populous district of the province, with an area of 3,447 km² (S. Ullah, Ullah, Tariq, Kasi, et al., 2025). The provincial capital (Quetta) has an arid to semi-arid climate with hot summers and cold winters. Nushki District is chosen as the study area for the current research study (Figure 1). District Nushki is located in the west of Quetta and bordered by Afghanistan through the Pak-Afghan border to the north, Mastung in the east, Kalat and Kharan in the south, and Chaghi district in the west. The district is located between longitudes 65°07'42" and 66°18'45" East and latitudes 29°01'51" and 29°52'37" North (Government of Balochistan (GoB), 2011). The total area of the Nushki District is 5,797 km2, and according to the 7th Population and Housing Census, the population of the district is 207,834 people, with an average household size of 6.6 (PBS, 2024).

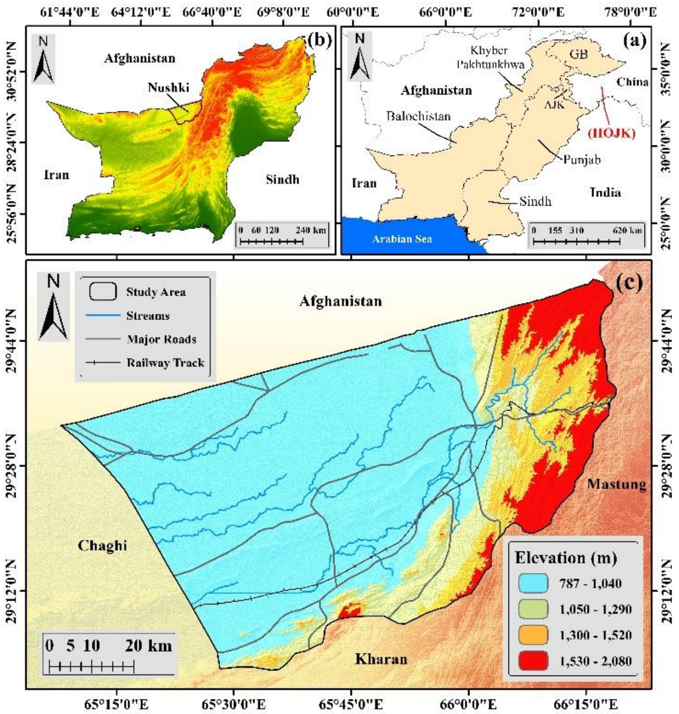

Fig 1. (a) National and provincial boundaries of Pakistan, along with association with neighboring countries, (b) Balochistan map with focus on the study area, and (c) the district boundary map along with elevation, major roads, streams, and railway track.

The annual average growth rate of the district from 2017 to 2023 is 2.53. The average elevation of the Nushki district is about 880 meters above sea level, and in the northern region of the district, there is a desert called Registan (Raig), which extends into Helmand province of Afghanistan (Rehman et al., 2019). The district's economy is based mostly on agriculture and the raising of livestock. The beds of perennial streams are home to the vegetation. Since the area is outside of the monsoon range, the 124 mm of annual rainfall largely falls during the winter. The long-term drought conditions in the district, which are marked by irregular rainfall and a drying karez irrigation system, have a significant negative impact on rural livelihoods. As a result, households have been forced to sell their assets, migrate, intake less food, and look for alternative sources of income rather than diversifying their cropping strategies (Tehmoor Rehman et al., 2019).

2.2. Data collection

Secondary data used in the present study were obtained from different sources. The national, provincial, and district boundary map, along with major roads, streams, and railway track, is obtained from the Spatial Decision Support System Lab (SDSSL). Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) 30 × 30 used to identify the elevation of the study area is obtained from the United States Geological Survey-USGS Earth Explorer (Table 1). Rainfall data for the study area are acquired using CHIRPS (Climate Hazards Group Infra-Red Precipitation with Stations) with a spatial resolution of 5.3 km through online sources. The flood extent of the study area was prepared using Synthetic Aperture Radar (SAR) data of Sentinel-1. Furthermore, the flood damage data is obtained from the National Disaster Management Authority (NDMA) and the Provincial Disaster Management Authority (PDMA).

Table 1. Data type, description, and sources used in the present study.

#	Data type	Description	Spatial resolution	Source
1	Shapefiles (.shp)	Shapefiles were used for the study area mapping.	--	SDSSL https://ncgsa.org.pk/spatial-decision-support-system-lab-sdssl/
2	SRTM DEM	DEM is used to prepare the elevation of the study area.	30 m	USGS Earth Explorer https://earthexplorer.usgs.gov/
3	Rainfall	CHIRPS monthly data is used to prepare the rainfall graphs.	5.3 km	CHIRPS https://www.chc.ucsb.edu/data/chirps
4	Flood extent	Sentinel-1 SAR data is used for flood extent mapping	10-20m	Sentinel-1 SAR https://www.earthdata.nasa.gov/data/instruments/sentinel-1-c-sar
5	Flood damages	Flood damage assessment	--	NDMA https://www.ndma.gov.pk/
6	Flood damages	Flood damage assessment	--	PDMA https://www.pdma.gob.pk/

2.2. Data processing and analysis

Along with flood extent mapping, the present study examines the existing literature on the 2022 floods in the Nushki district of Balochistan. The collected data was further processed and analyzed using different software. Microsoft Excel and CorelDRAW were used to generate attractive tables and graphs for the present study area. Google Earth Engine (GEE) was employed to assess the flooded areas in the Nushki district using remote sensing data. The flood extent was further exported to a geographic information system (GIS) environment for map-making. Finally, maps were produced using ArcMap 10.8.2. The detailed methodological framework followed for the present study is shown in Figure 2.

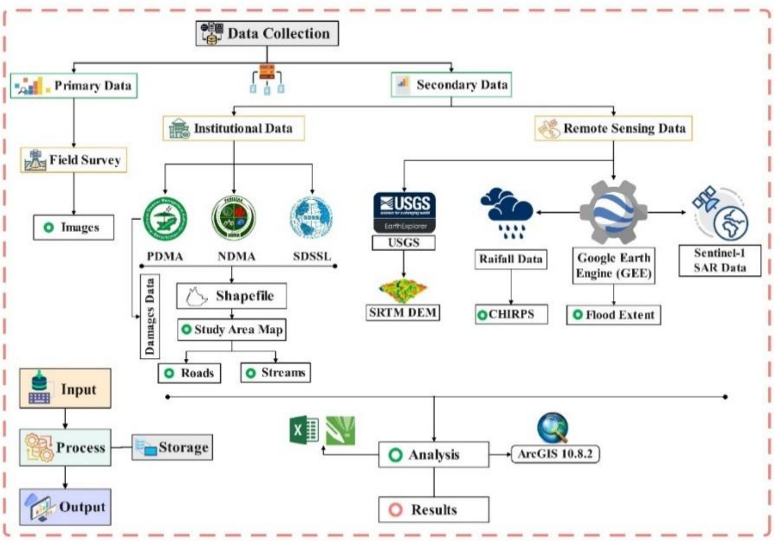

Fig 2. The detailed methodological framework is followed for the present study.

3. Results and Discussion

3.1. Rainfall distribution

Rivers overflow or surface flooding occurs when rainfall volume or intensity surpasses drainage capacity. In small catchments such as mountain torrents, intense rainstorms can cause unexpected floods. Flood production is primarily driven by rainfall intensity and other characteristics, such as duration, spatial distribution, and frequency; however, hydrological responses also substantially depend on land cover, soil moisture, watershed antecedent conditions, and catchment geometry (Sharma et al., 2018). Uncertain increases in rainfall extremes can result in disproportionately large floods in some dry catchments, whereas there is a roughly linear connection between rainfall and runoff in wet catchments with saturated soils (Breinl et al., 2021; Sharma et al., 2018). The consequences of climate change are more severe and far-reaching, compared to a few decades ago. Pakistan is most vulnerable to flooding (Shakeel Mahmood et al., 2024). The annual rainfall distribution of 2022 for Pakistan was obtained from CHIRPS (Climate Hazards Group Infra-Red Precipitation with Stations) through Google Earth Engine (GEE) (Figure 3). The maps in Figure 3 clearly show that District Nushki received less rainfall compared to the north and north-eastern parts of Balochistan. The total rainfall, maximum rainfall, and rainy days of 2022 in the Nushki district are shown in Figure 4. District Nushki, including other parts of Balochistan, receives very little rainfall in its regular pattern. However, in the months of June-August, the number of rainy days increased in 2022 (Figure 4). This led to catastrophic floods in Nushki and its adjoining areas in 2022. These floods have disrupted roads, communication lines, and crops.

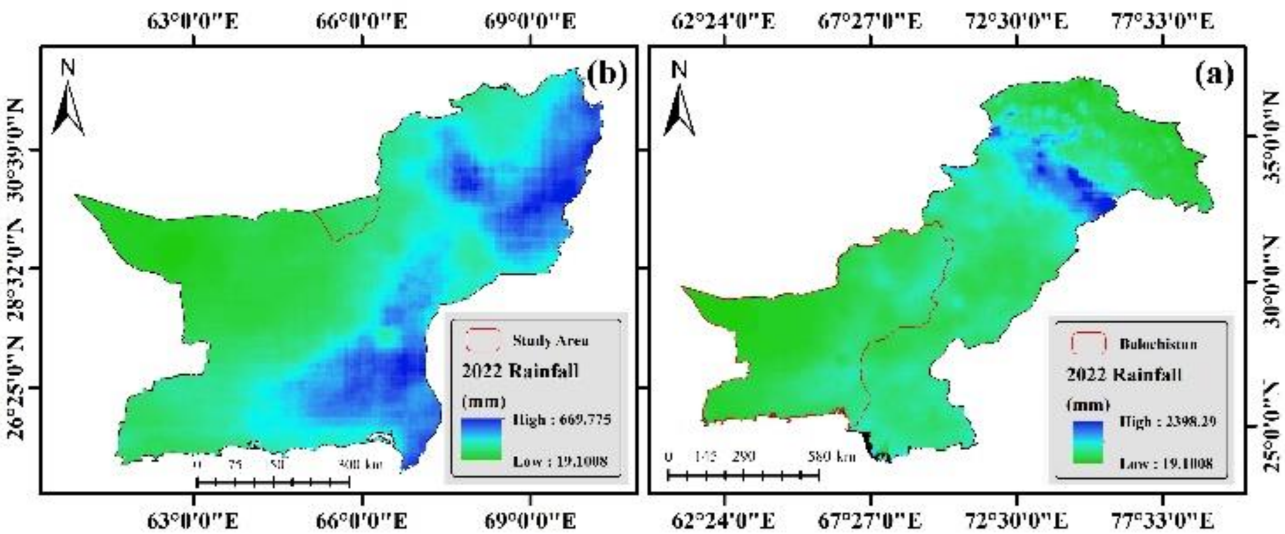

Fig 3. (a) 2022 rainfall distribution in Pakistan, (b) rainfall distribution in Balochistan with focus on the study area.

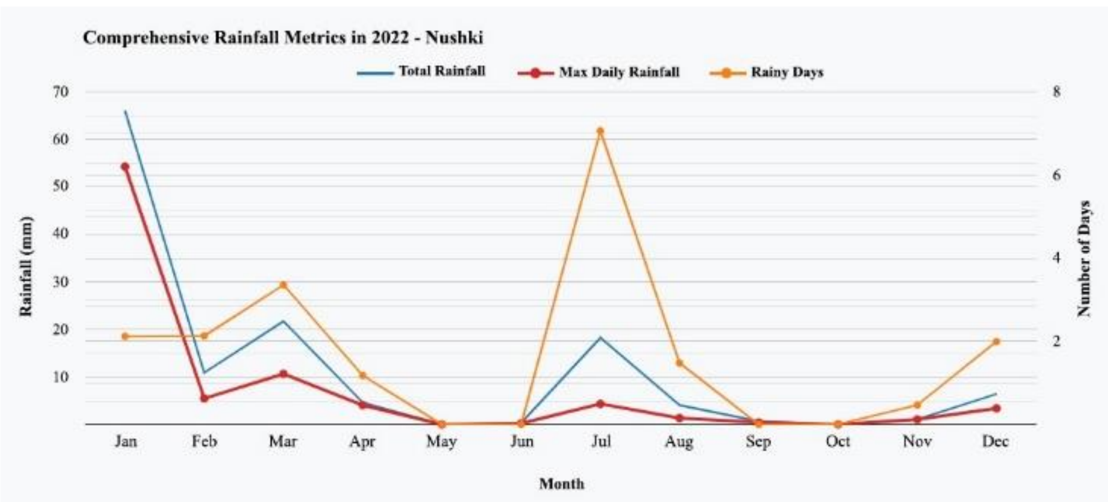

Fig 4. The total rainfall, maximum rainfall, and rainy days of 2022 in the Nushki district.

3.2. Rainfall distribution

Sentinel-1 satellite data were used for the flood extent mapping in 2022 for the study area. The flood extent mapping has been performed on Google Earth Engine (GEE), a cloud-based platform. Sentinel-1 SAR imagery is used because of its cloud-penetrating capabilities and suitability for flood mapping in all weather conditions. The resulting flood extent was visualized over the shapefile (.shp) of the study area. The flood extent raster was exported to Google Drive at 10-meter spatial resolution for further analysis in ArcMap 10.8.2 software. The flood extent in the study area is depicted with red color (Figure 5). Flood extent in the study area is shown by red color and is mostly found in the Daak Sub-Tehsil areas of the study area, which is reliable. This may be because the elevation of the whole Daak sub-Tehsil is low (800 meters) as compared to the Nushki sub-Tehsil.

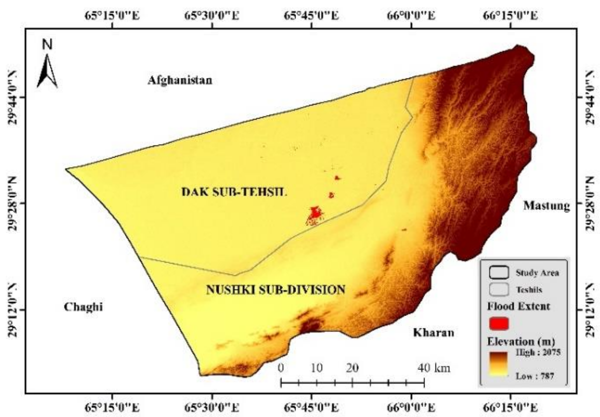

Fig 5. 2022-Flood extent in the study area.

3.3. 2022-Flood Impacts Assessment in Nushki

3.3.1. Impacts on Human Life

Flash floods occurred in Nushki District in July 2022, resulting in at least one male and three children losing their lives, and several injuries being recorded in other areas. The flooding also caused severe damage to the infrastructure (Table 2) (Provincial Disaster Management Authority (PDMA), 2022a). The Provincial Disaster Management Authority (PDMA) surveyed the study area from 12-17 August 2022 and assessed 62 flood-affected villages, where 31% of the human population was affected by the 2022 floods (Provincial Disaster Management Authority (PDMA), 2022b). Flooding turns short-lived water inundation events into long-lasting human crises that undermine social cohesion, economic stability, health, and well-being. This emphasizes how urgently vulnerable areas like the study area require coordinated disaster preparedness and recovery plans.

Table 2. Human casualties in the study area.

Causalities			Injured		
Male	Female	Children	Male	Female	Children
01	-	03	02	-	03
04			05		

Source: PDMA (2022)

3.3.2. Impacts on the Livestock Sector

The livestock sector was badly disrupted by the floods in Pakistan in 2022, endangering food and economic security in the flood-affected areas. A total of 2,229 livestock were lost in the study area because of the severe floods of 2022 (Provincial Disaster Management Authority (PDMA), 2022a) (Figure 6). These losses resulted in permanent revenue decline, widespread food insecurity, and increasing poverty in rural and tribal areas where livestock is the main source of wealth and nutrition. The disaster thus qualifies as both an acute humanitarian emergency and a long-term livelihood crisis necessitating focused rehabilitation efforts, such as veterinary support, fodder provisioning, and restocking programs.

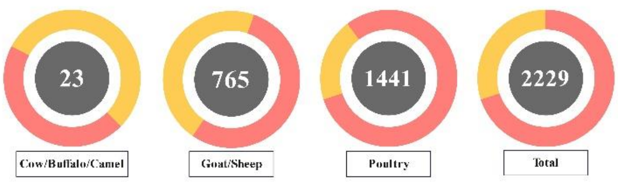

Fig 6. Livestock damages in the study area (PDMA, 2022)

3.3.3. Impacts on Infrastructure

The infrastructure sector was also damaged by the 2022 floods, isolating settlements and removing vehicle access tracks in the study area. Many locals were thus left temporarily without a place to live. Flash floods in the Qadir Abad area of the study area destroyed more than 40 mud-brick houses and damaged several more, forcing people to relocate and making houses uninhabitable (Saleem Shahid & Syed Irfan Raza, 2022). Other affected areas, where infrastructure was damaged, include Daak, Anam Bostan, Mengal Abad, and the Bazar areas (Figure 7). The floods of 2022 caused massive damage to houses in the study area, either completely or partially destroying them. The destroyed houses in the study area numbered 4,763, including 2,597 that were fully destroyed and 2,166 that were partially destroyed (Provincial Disaster Management Authority (PDMA), 2022a). Other damaged infrastructure in the study area includes 12 km of roads and 4 bridges.

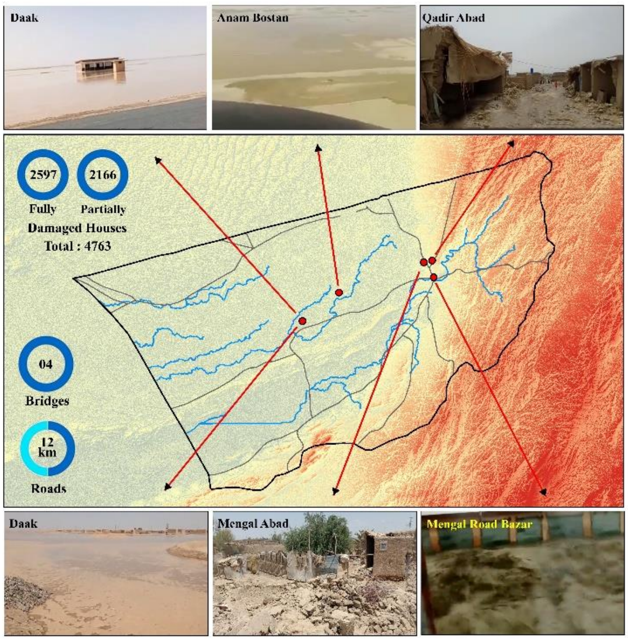

Fig 7. The infrastructure sector losses in the study area (PDMA, 2022)

3.3.4. Impacts on Agriculture

The agricultural sector was severely damaged by the floods in Pakistan in 2022, with long-term effects on food security, farmer livelihoods, and the overall rural economy. More than 200,800 acres (~81,200 hectares) of agriculture were destroyed in Balochistan, and the horticultural and orchard sector, which includes grapes, apples, peaches, and dates in the region, was also badly impacted. Particularly, in some places, losses in date orchards reached 90%. Estimates of the cost of provincial agricultural damage vary from Rs 4.9 billion Pkr to Rs 98 billion Pkr, indicating the extent of losses in districts such as Loralai, Washuk, and Nushki (Amin Ahmed, 2022). Nushki was one of the highest crop/vegetable damage districts in Balochistan. A total of 2,783 acres of agricultural land was affected by the 2022 floods in the study area, and solar panel losses were 25 (Provincial Disaster Management Authority (PDMA), 2022a).

4. DISCUSSION

The use of Geographic Information Systems and Remote Sensing enabled us to prepare the flood extent map for the study area. Regarding the extent of floods in 2022, the results of this study revealed that the floods in 2022 were more severe in the Daak sub-tehsil of the Nushki District. This may be because the Daak sub-tehsil is at a low elevation as compared to the Nushki sub-tehsil, which has high-elevation mountains. Therefore, the precipitation received during 2022 on the Nushki sub-tehsil area was drained quickly to the Daak sub-tehsil and affected the livelihoods of the people there. (Hussain et al., 2023) found that the people of district Nushki, which is near the borders of Afghanistan, have faced multiple natural hazards, including recurrent droughts and flash floods in 2022. Results of our study are in line with the study of (Shamshad Akhtar & Muhammad Rafique Dhanani, 2024), who found that Nushki was moderately affected by the 2022 floods.

Results also indicated that floods of 2022 had brought serious socio-economic impacts to the people living in District Nushki. The 2022 floods in Nushki brought about the deaths of about 3 children, and dozens of male and female were injured. A total of 2,229 livestock perished because of the 2022 floods. The floods also damaged 4,763 houses, either fully or partially. This may be because most of the people in District Nushki have used low-quality bricks, and muddy houses in the area were fully damaged because of the 2022 floods. Roads were severely disrupted by these floods. About 12 kilometers of roads were damaged to the extent that vehicles were unable to move on these roads. 4 bridges were also damaged as a result of these floods, which caused worry among the people to move to safer locations during floods. Floods had also damaged the crops and orchards, which were the mainstay of the majority of the farmers in the area.

Studies of Kiran & Jabbar (2022) also revealed that Nushki people faced serious concerns of food insecurity as a result of the 2002 floods. To make people safe and reduce the impacts of flood disasters in the future, there is a need for a proactive approach. Roads need to be elevated. Communication lines need to be strengthened. Evacuation shelter needs to be constructed to make sure the shelter for not only for human beings but also for livestock. These pre-disaster approaches will reduce the impacts of flood disasters in the future in the study area.

5. CONCLUSION

The floods of 2022 caused havoc in the whole of Pakistan and Balochistan, and especially the Nushki area was no exception to this phenomenon. The unusual increase in rainy days in 2022 resulted in severe flooding in the Nushki District. The low-lying sub-Tehsil of Daak was mostly affected because of its low elevation as compared to the Nushki sub-Tehsil. The floods affected the whole infrastructure, including damage to roads, buildings, electric poles, and other communication lines. These floods also affected the livestock and agriculture sector of the Nushki District. The floods also caused socio-economic impacts and affected the livelihoods of the communities through a shortage of daily food items. To safeguard the communities living in the vulnerable areas, the government authorities, including Disaster Management Authorities at the national level, provincial level, and district levels, need coordination among themselves. There is a need for planning and implementing pre-flood level management strategies that will make the communities resilient against flood disasters. Elevated shelter buildings need to be constructed to provide temporary shelter to the people in case of floods. These strategies, if fully implemented, will reduce the effects of future floods on the communities.

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Conflict of Interest: The authors declare that they have no conflicts of interest.

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Availability of Data and Materials: Data and materials for the present study will be available upon request from the corresponding author, Niamat Ullah (niamatullahza@gmail.com).

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Finding robust model for Urban Growth Prediction based on Land Use Land Cover Classification: A comparative study of CA Markov based Models LCM and MOLUSCE

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ABSTRACT

Background: Scientific information of future LULC is fundamental to make proper land use planning to fulfill the rising human demands and their wellbeing without causing lasting damage to environment.
Objectives: This paper is an attempt to identify the robust model among CA MARKOV based model Land Change Modeler (LCM (IDRISI) and MOLUSCE Model (QGIS Plugin) to predict urban growth for 2020 using LULC dynamics during 2000-2010 of Jaipur city, India, and Austin in America.
Methodology: The predicted maps were compared with observed map and accuracy was checked through mathematical equation as well as Kappa Index Statistic Assessment Tool of MOLUSCE Plugin.
Results: The results obtained through CA Markov method are robust and more accurate compared to MOLUSCE model. Therefore, it is highly recommended for government and non-government officials to study LULC dynamics and urban growth predictions in order to build urban resilience.
Conclusion: The study also highlights the importance of integrating road network data in improving prediction accuracy. These findings contribute to the development of sustainable urban planning strategies in rapidly growing cities.

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1. INTRODUCTION

Urban growth is one of the biggest environmental issues worldwide and an important development issue in developing countries like India. It has serious environmental, social, and economic implications in terms of food, clothing, housing, transport, pollution, sanitation, power, telecommunications, and health care. Continuous monitoring of land uses and land cover (LULC) changes for the past, present and predicting future changes are of utmost necessity for scientists, agriculturalists, urban planners, environmentalists, and policy makers to take timely actions to manage populace and related issues (Maurya et al. 2022). This work has been accomplished by studies around the world to plan proper land use policies and sustainable management (Guidigan et al. 2019). LULC prediction enable to build resilience in an urban area for upcoming catastrophes and climate shocks too.

The present study is an attempt to urban growth prediction using CA Markov and MOLUSCE models based on LULC integrated road network for Jaipur, India and Austin, USA. Urban growth prediction helps

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in urban planning, resource allocation, management, and conservation, and building resilience.
The objectives of present study are
(1) to find robust method of urban growth prediction amongst MOLUSCE and CA Markov
(2) to find differences in results of urban growth prediction using CA Markov and Molusce models
(3) to check the influence of Road network in predicting urban growth
For the above objectives, Jaipur City from India and Austin from USA are selected.

1.1. Literature Review

Urban growth prediction has been the subject of research for several reasons (Achmad et al. 2018; Al-Darwish et al. 2018; Clarke & Gaydos, 1998; Ebrahimipour & Farshchin, 2021; Guidigan et al. 2019; Jafari et al. 2016; Jayasinghe et al. 2019; Liu et al. 2019; Mc Cutchan et al. 2020; Mosammam et al. 2017; Samat, 2009). Studies across the world tried to achieve greater insight in extracting data, monitoring, and predicting LULC or urban growth with the help of available and advancing technology. The integration of RS and GIS proved useful in extracting accurate data and to process it for LULCC and its analysis. The prediction of LULC is achieved by different models available either as integrated software's or plugins. Mosammam et al. (2017) used a spatial approach through Idrisi Selva to quantify urban sprawl in Qom, Iran. Clarke & Gaydos, (1998) employed a combination of satellite data and a Loose-Coupling automation model based on Scale-independent classical cellular automation to predict urban expansion in San Francisco, Washington, and Baltimore. Semantic-based Urban Growth Prediction was done by Mc Cutchan et al. (2020). Another study came from Maurya et al. (2016) to investigate and predict urban growth in urban Jaipur. They used Toposheets from the India Geological Survey combined with Landsat MSS, TM, and ETM + data to prepare LULC maps while 2021 map was predicted through multilayer perceptron data. The SLEUTH is another model used to predict urban expansion and is employed by Liu et al. (2019) for East China. Jat et al. (2017) used the SLEUTH Model to anticipate the urban expansion of Ajmer city using Land Cover Deltatron (LCD) with Urban Growth Model (UGM).
CA Markov model is also employed to predict urban growth for Seberang Perai area in Penang State, Malaysia (Samat, 2009), Gilan, Iran (Jafari et al. 2016), Banda Aceh, Indonesia (Achmad et al. 2018), IBB city of Yemen (Al-Darwish et al. 2018), in Bojnourd, North Khoasan (Ebrahimipour & Farshchin, 2021). While CA Markov Model to predict urban growth was employed by (Aithal et al. 2013) for Greater Bangalore, India, in Vijayawada, Andhra Pradesh, (Kusuma & Pradesh, 2017), in fast urbanizing cities of India including Mumbai, Delhi, Chennai, Pune, and Coimbatore (Bharath et al. 2018), in Pune, Maharashtra (Yadav et al. 2019). The projection of urban growth for Chennai, Tamil Nadu, India was carried out using a neural network coupled agents-based Cellular Automata model (Aarthi & Gnanappazham, 2018). Guidigan et al. (2019) studied the LULC dynamics and its impacts in Benin Republic using MOLUSCE model and validate the results by comparing the observed and predicted LULC maps.
In a study by Mondal et al. (2016), urban development was studied and predicted for Guwahati, India and used Kno, K Location statistics and K Location strata statistics for validation of predicted maps. Most of the previous studies focused only on LULC prediction but failed to present area statistics under each class and validation and accuracy assessment was not done properly.
Furthermore, no such study except (Jayasinghe et al. 2019) has conducted a comparison to identify the most robust technique to make urban growth prediction and such studies in India are very limited.
A study conducted by Mountrakis & Triantakonstantis, (2012) reviewed available urban growth projection models. It found that Spatial Autocorrelation and Heterogeneity models are mainly used with several underlying modelling methods like CA, ANN, Fractal Modeling, Decision Trees Regression, and Agent-Based Modeling. Of all these models, Cellular Automata was discovered to be the most extensively used method as it was employed by 83 percent of the academics, followed by Logistics Regression (23 %), ANN (12%), Fractal Modeling (10%), Agent-Based Modeling (9%), and Decision Trees (2%). Jayasinghe et al. (2019) did a comparative evaluation of urban growth models (FUTURES, SELUTH, and MOLUSCE). The study concluded that MOLUSCE is easy to implement with limited data and have acceptable accuracy, FUTURES is a robust, customizable, and flexible to incorporate policy scenarios while SLEUTH is extensively used. Study further revealed that it is not

fair to compare which model perform better than the other considering the variations of implementation, techniques, and procedures.

2. METHODOLOGY

2.1. Data Used

2000 and 2010 Landsat 5 TM and 2020 Landsat 8 OLI data were acquired from United States Geological Survey (USGS) having spatial resolution of 30 m for both Jaipur and Austin. These data have geographical coordinate system (GCS) based on the World Geodetic System (WGS 84). The other essential data namely Road Network was acquired from Open Street Maps, while Digital Elevation Model (DEM) from Earth Data Portal of NASA. From these data sets other raw data (road distance, slope, urban distance) are prepared. Table 1 and Fig. 1 showed the raw and final data used in this study.

Table 1. Raw data used in this study.

S. No.	Data Type	Source	Acquiring Date (yyyy.mm.dd.)		Path & Raw		Resolution
			Jaipur, India	Austin, USA	Jaipur, India	Austin, USA	
	Satellite data						
1.	Landsat 05 TM	USGS	2000.04.14	2000.04.31	147 / 41	027/039	30 m
2.	Landsat 05 TM	USGS	2010.04.10	2010.05.03	147 / 41	027/039	30 m
3.	Landsat 08 OLI	USGS	2020.04.21	2020.04.12	147 / 41	027/039	30 m
	Essential data						
4.	Road Network Map	OSM Data	-		-		-
5.	DEM	Aster Dem	-		-		90 m

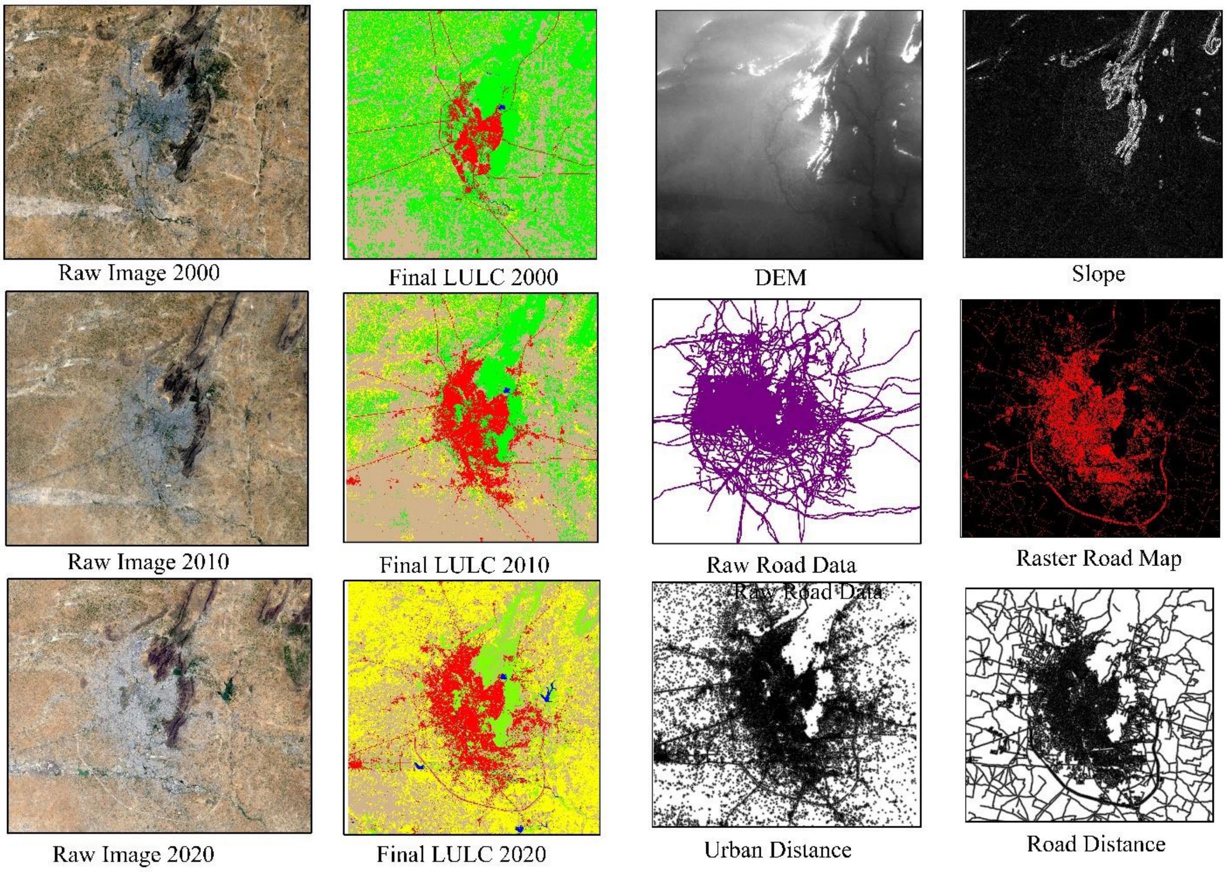

Fig 1. Data visualization used in Analysis

Table 2a. LULC data accuracy through; a)Accuracy assessment and , b) Kappa statics (Jaipur, India)

a) Accuracy Total			
Classes	2000 Producer/User	2010 Producer/User	2020 Producer/User
Vegetation	85.71/90	95/95	93.33 /93.33%
Agriculture	100/95	94.44/85	88.89%/100%
Barren	100/100	90.48/95	93.75%/93.75%
Built-up	100/90	100/100	93.75%/93.75%
Water	100/100	100/93.75	100%/ 93.75%
Overall	93.88%	93.75	93.75%
b) Kappa statics			
Vegetation	0.8727	0.9368	0.8462
Agriculture	0.9380	0.8154	1.0000
Barren	0.9364	0.9360	0.9219
Built-up	1.0000	1.0000	0.9219
Water	0.8775	0.9259	0.9231
Overall Accuracy	0.9236	0.9221	0.9219

Table 2b. LULC data accuracy through; a)Accuracy assessment and , b) Kappa statics (Austin, USA)

c) Accuracy Total			
Classes	2000 Producer/User	2010 Producer/User	2020 Producer/User
Vegetation	90.48%/95%	78.26%/90%	100 /90.28%
Agriculture	94.74%/90%	85.71%/90%	100%/100%
Barren	86.36%/95%	100%/100%	100%/100%
Built-up	95%/95%	94.44%/89.47%	84.21%/100%
Water	100%/95%	100%/94.74%	100%/ 100%
Overall	93.40%	91.43%	94.17%
d) Kappa statics			
Vegetation	0.9376	0.8720	0.789
Agriculture	0.8782	0.8750	1
Barren	0.9369	1	1
Built-up	0.9384	0.8730	1
Water	0.9391	0.9365	1
Overall Accuracy	0.9192	0.8953	0.8992

2.2. Data Processing

Data processing consisted of classification of Landsat data products in ArcMap 10.7 and Erdas Imagine 15. LULC classes considered in the process include water bodies, vegetation, urban, barren land and agriculture. The essential data was processed in ArcMap which was first converted into 8-bit unsigned thematic format through Erdas Imagine. After classifying data into Land use land cover classes, data was processed in MOLUSCE and LCM for predicating 2020 LULC maps. The predicted map of 2020 each with LCM and MOLUSCE was validated with observed LULC map of 2020 and finally the results obtained were compared in two ways. Firstly, the results were validated through mathematical equation involving area computation from predicted and observed 2020 LULC map and secondly through kappa index statistics validation function of MOLUSCE model. The methodology flow chart of the study is given in figure 2.

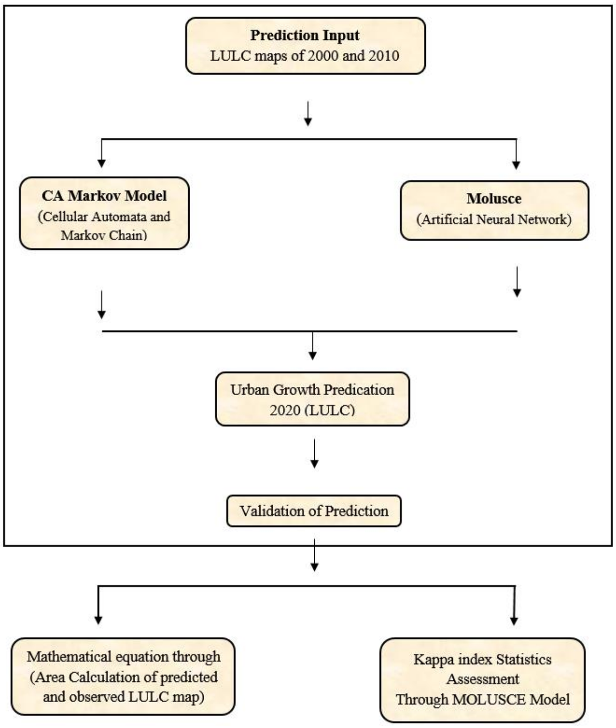

Figure 2. Methodology flow chart

2.3. Prediction and Validation Method of LULC

In this study, LULC prediction for 2020 was carried out using 2000 and 2010 validated supervised classified LULC images. For which Cellular Automata Markov chain and a cellular automaton multi-layer perceptron artificial neural network (MLPANN) dependent MOLUSCE (Modules for Land Use Change Evaluation) and LCM models based on great significance of LULC transitions were used. LCM model is an integrated software of Idrisi Selva while MOLUSCE model is a plugin for QGIS. Both these models are constructed to analyze and forecast present to future LULC and are based on spatial data analysis with different techniques. Both models (LCM, and MOLUSCE) support Cellular Automata, The Land Change Modeler (LCM) module in TerrSet (formerly marketed as IDRISIS) represents a comprehensive decision-support platform for detecting, modeling, and projecting land cover transitions and MOLUSCE demonstrate that this QGIS-based plugin integrates cellular automata mechanisms with transition probability matrices derived from paired historical LULC maps and spatially continuous explanatory variables such as distance to roads, water bodies, and urban settlements. Regarding the outputs, LCM produced thematic data in unsigned 8-bit format while MOLUSCE produced CCI file which is a single layer or grey scale imagery and is to be converted into unsigned 8-bit format. The following are the steps involved in predicting LULC change:

1. Variable selection: to improve the model's accuracy, distances to important roads were utilized as a variable.
2. Change detection: transition matrices and change maps were created in this step, which were then employed in the modelling process.
3. Transition potential estimated for 2000-2010 through the MLP-ANN and Markov approaches generates separate probability matrices that supports the prediction model.
4. Prediction of land use and land cover: MOLUSCE's LCM and MLP-ANN simulation tabs were used to forecast 2020 LULC.

The results from change detection, variable selection and transitional potential through LCM mentioned above were published earlier in the form of a journal paper entitled "Land use/land cover dynamics study and prediction in Jaipur city using LCM model integrated with road network" authored by (Maurya et al. 2022). While transitional potential through MLP-ANN and LULC prediction for Jaipur (India) and Austin (USA) cities is carried out in present study.

2.4. Study Area

This study focused upon Jaipur City, Rajasthan India and Austin, USA to assess the performance of LCM and MOLUSCE urban growth prediction models. Jaipur city has seen an unprecedented population growth on account of it being an oldest, seventh largest, tourist destination, world heritage site and one of earliest planned city of India. With a mere count of 294,021 inhabitants in 1950 the population now estimated to have risen to 4,007,505 in 2021 (Maurya et al. 2022). Austin established on December 27, 1839, is the 11 most population city in USA, fourth most populous city in Taxas and the second most populous state capital city. As of 2021, Austin had an estimated population of 964,177, ("City and Town Population Totals: 2020-2021". United States Census Bureau. Retrieved September 7, 2022.) up from 961,855 at the 2020 census ("Austin's Population Continues Another Decade of Growth According to U.S. Census Bureau | AustinTexas.gov". *www.austintexas.gov*. Retrieved October 10, 2022.).

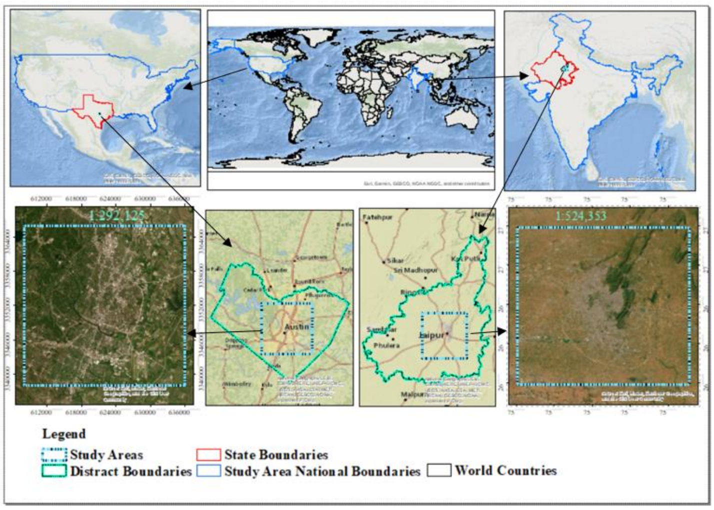

Fig 3. Study area location map

3. RESULTS

3.1. Identification of LULC and its dynamics between 2000 to 2020

The land use land cover maps were prepared and classified into 5 classes, viz Vegetation, Agricultural, Barren, Built-up, and Water Body. The Jaipur city experienced drastic changes in LULC classes particularly in agriculture, barren and built-up during 2000–2020 (table 3). The changes in LULC have negative impacts on climate and environment through carbon sinks, intensity of runoff, loss of biodiversity, people, and their livelihood (Gidey et al. 2017; Hurni et al. 2005; Nourqolipour et al. 2014; Sang et al. 2011).

The analysis of land use conversion matrix showed that vegetation, agriculture, built-up and water bodies are all decreased at the expense of built-up or urban area. In 2000, the built-up area accounted for 110.68 km^2 (4.75% of total) which has increased to 225.47 km^2 (9.68% of total) in 2010 and 301.82 km^2 (12.9% of total) in 2020 (Maurya et al., 2022) at Jaipur. The estimated area under each class is given in table 2. Similarly, the built-up increased from 98.31 km^2 (12.55% of total) to 135.39 km^2 (17.28%) in 2010 and 210.42 (26.86%) in 2020. These results depicting that both cities are growing exponentially. Other classes have decreased vegetation, agriculture, barren, built-up, and water.

Table 3a. Matrix summary of LULC 2000, 2010 and 2020

Classes	Year 2000 Area in Km²	Year 2010 Area in Km²	Actual 2020 Km²
Vegetation	1252.36 (53.79%)	485.37 (20.85%)	306.22 (13.15%)
Agricultural	213.39 (9.16%)	284.25 (12.21%)	915.72 (39.33%)
Barren	749.53 (32.19 %)	1331.91 (57.20%)	791.05 (33.97%)
Built-up	110.68 (4.75%)	225.47 (9.68%)	301.82 (12.96%)
Water	2.37 (0.10%)	1.33 (0.06%)	13.52 (0.58)
Total	2328.33	2328.33	2328.33

Table 3b. Matrix summary of LULC 2000, 2010 and 2020, Austin

Classes	Year 2000 Area in Km²	Year 2010 Area in Km²	Actual 2020 Km²
Vegetation	606.88 (77.47%)	504.49 (64.40%)	469.47 (59.93%)
Agricultural	14.22 (1.82%)	87.15 (11.13%)	6.38 (0.82%)
Barren	49.33 (6.30%)	39.53 (5.05%)	82.90 (10.58%)
Built-up	98.31 (12.55%)	135.39 (17.28%)	210.42 (26.86%)
Water	14.65 (1.87%)	16.83 (2.15%)	14.22 (1.82%)
Total	783.41	783.41	783.41

Prediction and its Validation

MOLUSCE and LCM methods were used to predict LULC patterns in 2020 based on 2000 and 2010 LULC maps. To validate the results of prediction, the predicted and observed LULC maps of 2020 were compared through transition potential modelling and two different methods namely a mathematical equation and another was kappa index statistic (Kamusoko et al. 2009; Guidigan et al., 2019) were used. The first method uses mathematical equation (100-SQRT((Difference)^2), here are difference between observed and predicted LULC map of 2020 was used. According to this equation, LULC classes namely vegetation, agriculture, barren, water and has 74.97%, 34.48%, 49.77%, 88.61% and accuracy respectively when predicted through LCM model whereas 66.36%, 25.36%, %, 32.14%, 8.38% and as per MOLUSCE model, The prediction accuracy of built-up (urban) area was 88.92% as per LCM and 83.71% based on MOLUSCE at pre-defined level of 90.00% accuracy and 1.0 kappa coefficient of 2000 LULC while at 100% accuracy and 1.0 kappa of 2010 LULC data at Jaipur (Table 4). The low accuracy of some classes such as vegetation and agriculture land were due to the mixing of their pixel because these two classes reflected light in the same spectrum on a satellite image and were consequently identified as a single feature at several locations During the monsoon, vegetation area increases while bare land decreases, and this pattern is reversed during the winter season. Similarly, area under water also tends to increase due to excessive monsoonal rain. The newly constructed ring road was reflected as barren land on satellite images (Mourya et al. 2022). On the other hand, Austin has a good score in overall accuracy than the Jaipur which is 68.97% by LCM and 66.36% by MOLUSCE; whereas the classes (vegetation, agriculture, barren, water and built-up) results are 98.18%, 25.21%, 43.01%, 85.67% gained LCM and 94.65%, 23.96%, 41.69%, 83.69% gained MOLUSCE; the built-up (urban) accuracy was 92.79% obtained LCM and 87.85 % MOLUSCE model. The Austin city results are good enough, but we could get better results with recent high-quality datasets such as Sentinel 2 with 10 meters remote sensing satellite data cause the city's building as small which mostly covered by vegetation which resulted a bit low accuracy with 30 meters data. High resolution data could distinguish the vegetation and built-up area, but it also has temporal limitation (data available only after 2016). The other method of validating simulation accuracy used here was kappa index statistic, which is a validation function of MOLUSCE. Kappa statistics, Error Budget validation, and Error Map validation are the three forms of validation available in MOLUSCE. While kappa overall (Kovr), kappa histogram (Khisto), and kappa location (Kloc) are the three components of kappa statistics (Asia Air Survey and Next GIS 2017), whose equations are given below.

1. Kappa overall:

$$K = \frac{P\ (A) - P\ (E)}{1 - P(E)}$$

2. Kappa location

$$K_{loc} = \frac{P\ (A) - P\ (E)}{P\ max - P(E)}$$

3. Kappa histogram

$$K_h = \frac{P\ max - P(E)}{1 - P(E)}$$

Where $P(A) = \sum_{i=1}^{C} p_{ii}$, $P(E) = \sum_{i=1}^{C} p_{iT}p_{Ti}$, $Pmax = \sum_{i=1}^{C} \min\ (p_{iT,}p_{Ti})$ and pij is the i,j-th cell of contingency table, piT is the sum of all cells in i-th row, pTj is the sum of all cells in j-th column, c is count of raster categories.

According to LCM the accuracy in terms of Kovr was 0.330, Khisto was 0.587 and Kloc was 0.563 whereas according to MOLUSCE model these values were 0.206, 0.461, and 0.448 respectively at Jaipur. LCM obtained 0.429 Kovr, 0.842 Khisto, and 0.510 Kloc and MOLUSCE gained 0.390 Kovr, 0.718 Khisto, and 0.544 Kloc. Here, Jaipur has low Kappa accuracy cause Agriculture overestimated in actual 2020 LULC. We have not focused on agriculture class overestimation due our focus is for built-up or urban expansion and simulation for future). additionally pervious mentioned anthropogenic causes ring road southern corridor which can't be simulated by any model, water bodies area has been increasing which as well is also an anthropogenic cause due to it. The water area increased due to building concrete structures for Amanisha River, Kanota Dam water area and increasing level due to urban and industrial waste.

Table 4. Predicted Data Accuracy Assessment using Mathematical Equation in %

Class Name	CA Markov		Molusce	
	Jaipur	Austin	Jaipur	Austin
Vegetation	74.97	98.18	66.36	94.65
Agriculture	34.48	25.21	25.36	23.96
Barren	49.77	43.01	32.14	41.69
Built-up	88.92	92.79	83.71	87.85
Water	10.61	85.67	8.38	83.69

The observed and predicted 2020 LULC map from LCM and MOLUSCE are shown in Figure 4 and area statistics of each LULC class are given in Table 5. The comparison was done against observed LULC map of 2020. According to observed LULC map of Jaipur, vegetation covers 306.22 km^2 of area, agriculture covers 915.72 km^2, barren land occupies 791.05 km^2, built-up covers 301.82 km^2 and water occupies 13.52 km^2 in 2020. While prediction through MOLUSCE (ANN-MLP) showed that from 2010 to 2020, vegetation declined from 485.36 km^2 to 304.72 km^2 with a total decrease of 180.65 km^2, agriculture declined from 284.25 km^2 to 57.40 km^2 with the decrement of 266.85 km^2. Barren land has inclined from 1331.91 km^2 to 1614.88 km^2 with the increment of 1482.97 km^2 while surface water was decreased from 1.33 km^2 to 0.32 km^2. On the other hand, LCM prediction for 2020 showed a decrease in vegetation from 485.28 km^2 to 453.28 km^2 with a total decrease of 32.09 km^2. Land area under agriculture declined from 284.25 km^2 to 279.13 km^2 with decrement of -5.12 km^2. Barren land has also declined from 1331.91 km^2 to 1259.51 km^2 accounting to a decrease of 72.40 km^2 and surface water decreased from 1.33 km^2 to 1.16 km^2. As per supervised LULC Map of Austin city classes coverage portion are vegetation 469.47 km^2, agriculture, 6.38 km^2, barren 82.90 km^2, built-up 210.42 km^2, and water 14.22 km^2 in 2020; while the models simulated trough MOLUSCE are 518.03 km^2, 88.20 km^2, 39.24 km^2, 121.73 km^2, and 6.15 km^2 respectively. The LCM model gained 460.94 km^2, 75.28 km^2, 35.65 km^2, 195.27 km^2, and 16.26 km^2. The LCM simulation from 2010 to 2020, vegetation declined from 504.49 to 460.94 with the decrement of 43.55, agriculture declined 87.15 to 75.28 with decrement of 11.87, barren declined from 39.53 to 35.65 with decrement 3.88, and water declined 16.83 to 16.26 with decrement with 0.57. Similarly, the MOLUSCE model simulation shows that vegetation decreased from 504.49 to 498.03 with decrement of 6.46, agriculture decreased from 87.15 to 86.2 with the decrement of 0.95, barren decreased from 39.53 to 39.24 with decrement of 0.29 and water decreased from 16.83 to 16.15 with decrement of 0.68. Both models reflect that the vegetation, agriculture, and water bodies have declined during 2010 to 2020 simulation in both cities.

The urban area has increased from 225.47 km^2 in 2010 to 351.00 km^2 in 2020 (MOLUSCE) with increment of 125.53 km^2 and according to LCM the increase was

109.78 km² accounting to 335.25 km² (Table 2) in Jaipur. However, the built-up area in 2020 as per observed LULC map was 301.82 km^2 with an accuracy of 94.74%, which according to mathematical equation (Accuracy value *100/ Accuracy percentage) would equal to 318.57 km² if its 100% is calculated. Similarly, as per kappa statistics it has an accuracy of 0.87 or 87% meaning that built-up area would be 366.17 km² if its 100% is calculated. This suggests that the 2020 predicted LULC maps had high accuracy in estimated nearly the same urban growth as obtained from observed 2020 LULC map. Similarly, urban area has increased from 135.39 (2010) to 141.73 (2020) by MOLUSCE projection with increment of 6.34 and LCM projection shows that increased to 195.27 in Austin. However, the urban (built-up) area in 2020 as supervised LULC map 210.42 with an accuracy of 100% (as per accuracy report) and kappa accuracy also 1 which represents 100 %. Thus, the LCM obtained 92.79% and MOLUSCE obtained 87.85 %. Both cities and models experiment shows that the LCM outperformed with accuracy for urban predication.

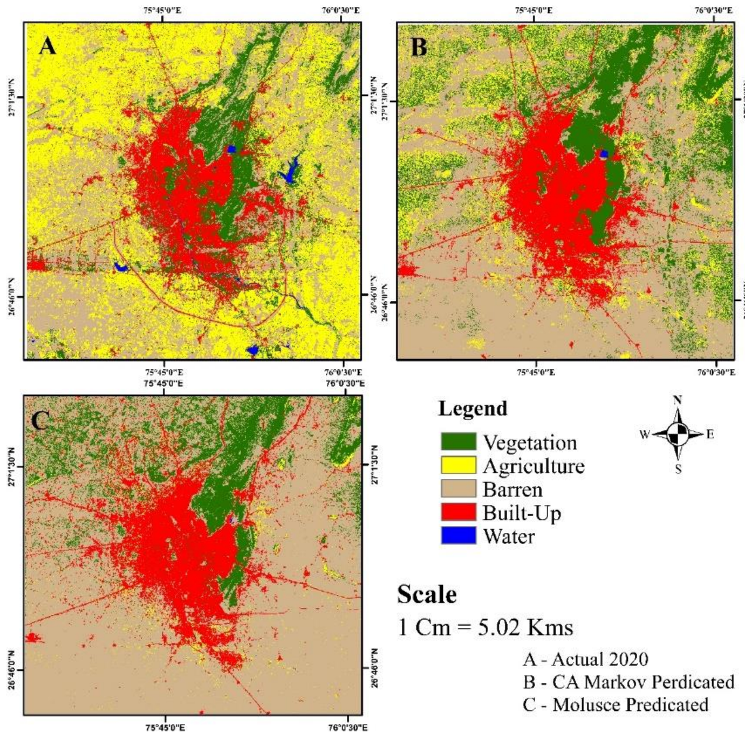

Fig 4. Predicated and Observed 2020 LULC Maps of Jaipur, India.

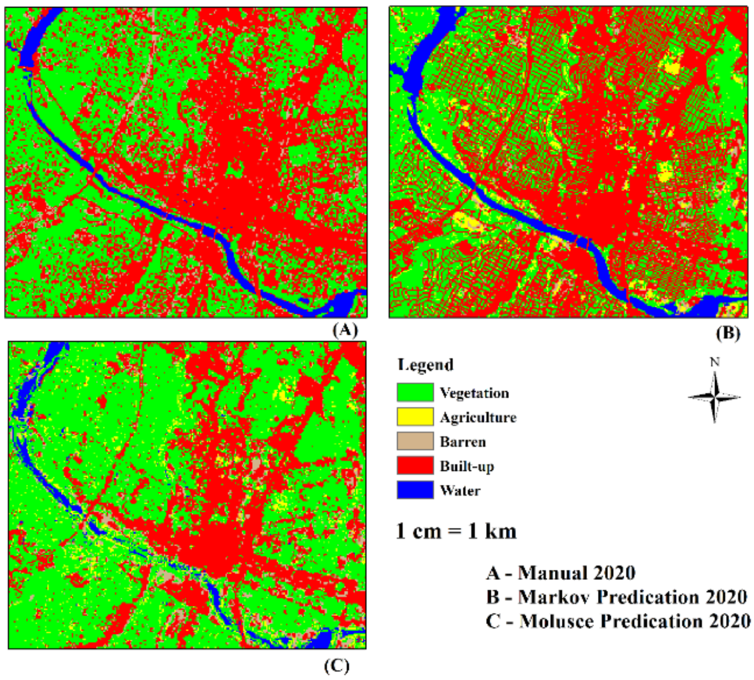

Fig 5. Predicated and Observed 2020 LULC Maps of Austin, USA.

Table 5 (A). Results from the Models, Jaipur India

Class Name	Observed 2020	Molusce Prediction	CA Markov Prediction
Vegetation	306.22	304.72	453.28
Agriculture	915.72	57.40	279.13
Barren	791.05	1614.88	1259.51
Built-Up	301.82	351.00	335.25
Water	13.52	0.32	1.16

Table 5 (B). Results from the Models, Austin, USA.

Class Name	Observed 2020	Molusce Prediction	CA Markov Prediction
Vegetation	469.47	518.03	460.94
Agriculture	6.38	88.20	75.28
Barren	82.90	39.24	35.65
Built-Up	210.42	121.73	195.27
Water	14.22	16.15	16.26

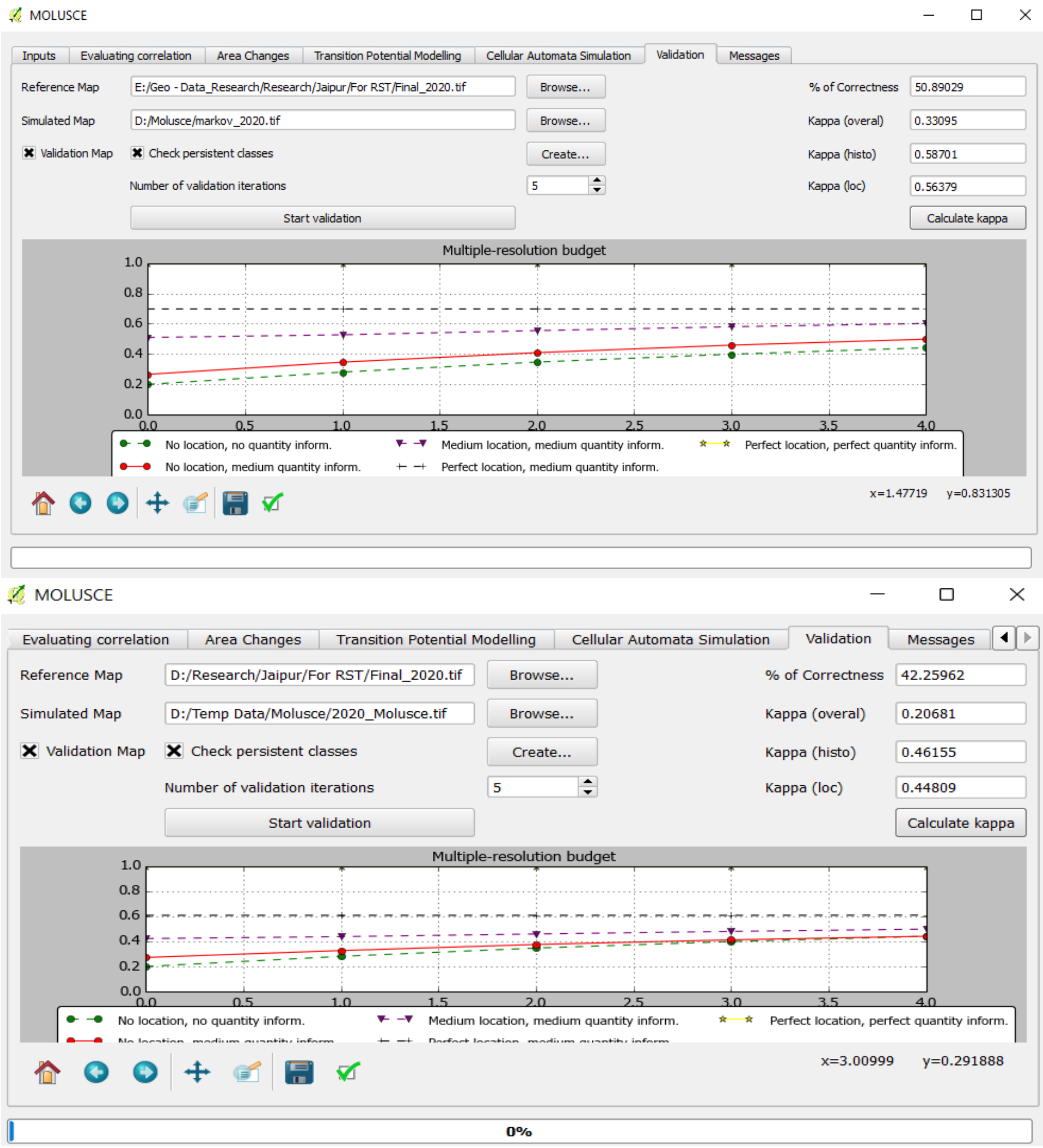

Figure 6 (A). Validation function of Molusce model (Jaipur, India).

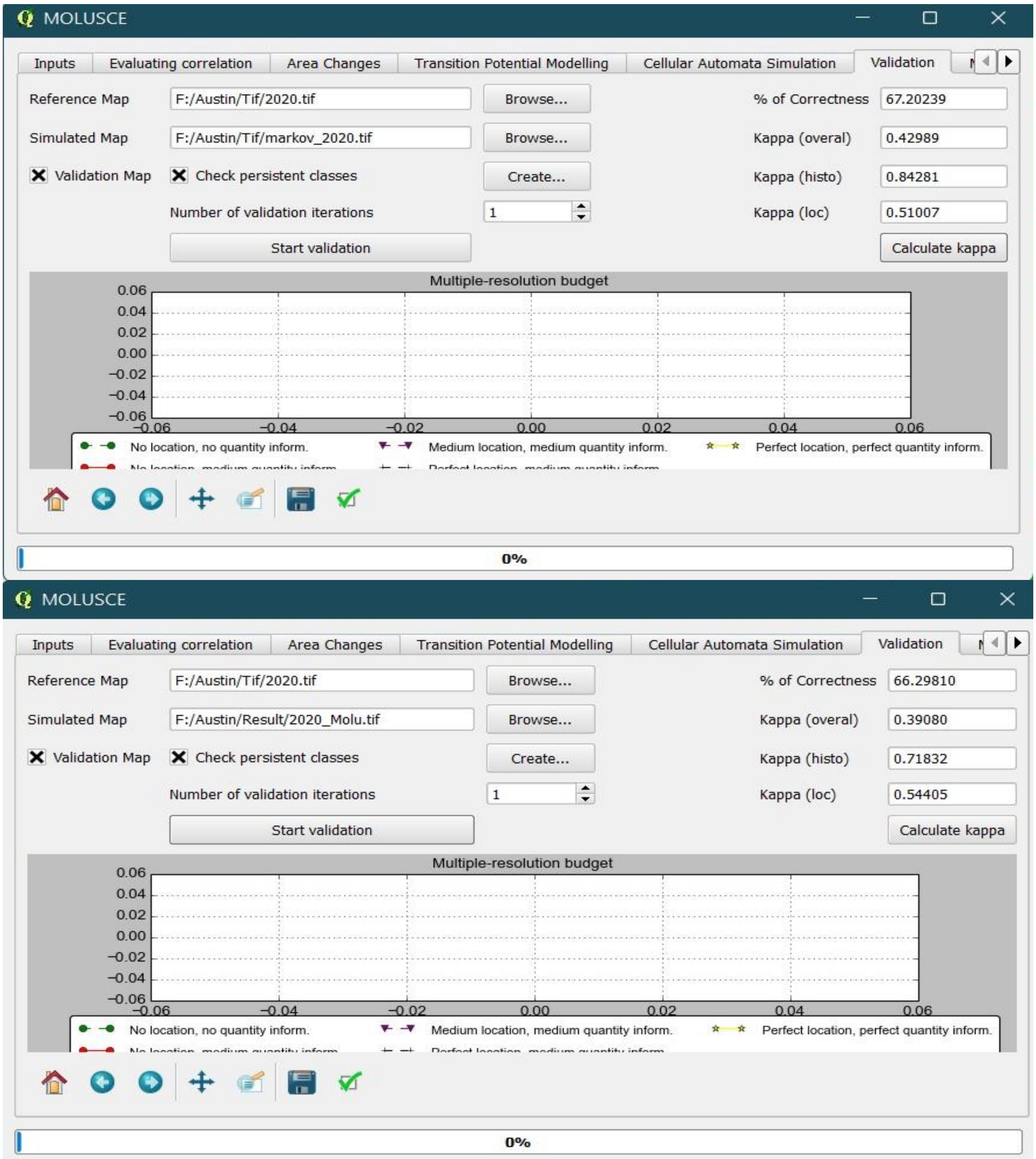

Figure 6 (B). Validation function of Molusce model (Austin, U.S.A).

Because of the fast growth of built-up area, and human activities, there was an overall loss of LULC classes such as agriculture, vegetation, barren ground, and water bodies from 2010 to 2020. These findings point to a concerning future landscape in Jaipur, which will be the outcome of completely damaged natural vegetation. Furthermore, it emphasizes the significance of landscape management and development. MOLUSCE and LCM models were integrated with GIS technology to successfully simulate land use change in Jaipur and Austin Cities utilizing land use maps (2000, 2010, and 2020) and road network data. The findings of the used model are satisfactory, but this study identifies that LCM gives more robust results in comparison to MOLUSCE. In LCM, accuracy of the prediction depends upon the accuracy of input data be it road network, DEM or any other and it works well with these data. Any change in assignment of hierarchies to data will also affects the results of LCM prediction. Unlike LCM, MOLUSCE model do not require additional data such as road network to run the model. However, it has three methods of evaluating correlation which affect, it's prediction results and accuracy. Cramer's coefficient yields better results in comparison to other two methods namely correlation and joint information uncertainty.

4. CONCLUSION

This research work identifies the more robust model among LCM and MOLUSCE to predict urban growth taking the example of Jaipur (India) and Austin (USA) cites. Cellular Automata–Markov Chain (CA–

Markov) within the Land Change Modeler and the multilayer perceptron (MLP) artificial neural network–based MOLUSCE framework were effectively employed to simulate future land use/land cover (LULC) change scenarios in both cities. Additionally, the accuracy of the forecasted LULC map for 2020 was evaluated using a mathematical calculation and the kappa index statistics. This study revealed that LCM model out functions MOLUSCE model used here because it worked on cell conversion and generated prediction based on cell change analysis. The forecasted LULC map depicts the likely spatial and quantitative change in LULC in the future. It showed a decline in vegetation (32.09 km^2)), agriculture (5.12 km^2)), barren land (72.40 km^2) and surface water (0.17 km^2) during 2010-2020. Whereas the built-up area found to have increased to (109.78 km^2) during the same period.

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Delineation of Groundwater Potential Zones Mapping Using MIF and Remote Sensing Techniques in an Agricultural Production Area Karezat Tehsil, District Pashin of Pakistan

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ABSTRACT

Background: The most important supply of freshwater on Earth, groundwater is essential for meeting industrial, agricultural, and residential demands. Pakistan's limited groundwater supplies are under tremendous strain due to the country's fast population increase and agricultural expansion.
Objectives: This study's principal goal was to use geospatial tools to identify groundwater potential zones (GWPZs) in a Pakistani agriculturally productive area. The study's objectives were to classify the region according to its groundwater potential and evaluate the variables affecting groundwater occurrence.
Methodology: The study used ArcGIS 10.8 software to integrate geospatial analysis with the Multi-Influencing Factor (MIF) technique. Geology, soil type, slope, rainfall, lineament density, drainage density, and land use/land cover (LULC) were the seven thematic layers that were chosen as the main factors affecting groundwater availability. These factors were combined using weighted overlay analysis to create a map of the groundwater potential zone.
Results: There are three main groundwater potential zones in the study area: high, poor, and very poor. A little over 315 km² of the land was found to be in the high potential zone, 1181 km² in the low potential zone, and 30 km² in the extremely poor potential zone, according to the spatial distribution. The findings demonstrate how the groundwater supply varies geographically throughout the research area.
Conclusion: The study shows that using the MIF method in conjunction with GIS and remote sensing techniques offers a dependable and effective way to identify possible groundwater zones. The results can help planners, legislators, and managers of water resources develop and manage groundwater sustainably, especially in areas where water shortage is growing.

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1. INTRODUCTION

Water is essential to life on Earth and has a major impact on every stage of our environment (Westall & Brack, 2018). The need for groundwater is growing as a result of the current surface water supplies' inability to meet all of the demands for agriculture, household, and industrial use (Priyan & region, 2021). Increased ground water use and surface water shortages are the results of economic growth, climatic change, high population density, and unequal distribution of water resources (Arsiso et al., 2017). It is estimated that around 30.1% of freshwater on Earth comes from groundwater. It is commonly used for household purposes and is one of the most important sources of freshwater (Mishra, 2023). Just 3% of the water on Earth is thought to be fresh, with the remaining 97% being ordinary saline water that is unfit for human consumption. Glaciers and ice sheets hold 68.7% of the fresh water that is available (Mishra, 2023). The world's need for freshwater resources has grown dramatically as a result of fast industrialization and population expansion. As a result, groundwater extraction is now a crucial component of many water management strategies, especially in rural areas (Siegel, 2021).

A region's "groundwater potential" is the quantity of groundwater that is accessible there and depends on a number of hydrogeological and hydrological parameters (Díaz-Alcaide & Martínez-Santos, 2019). The amount of freshwater on Earth is constantly abundant, although it fluctuates in time and location and isn't always appropriate for all purposes (Fleming, 2019). In both natural and artificial settings, groundwater is a vital natural resource for the reliable and affordable supply of drinkable water (Scanlon et al., 2023). Thus, groundwater supplies are essential to both terrestrial and marine ecosystems as well as human well-being (Naiman & Dudgeon, 2011). Presently, over 34% of the total yearly water supply comes from groundwater. For the sustainable use of this natural resource, effective groundwater management is therefore crucial (Scanlon et al., 2023).

Remote sensing (RS) and geographic information systems (GIS) are useful instruments for identifying possible groundwater locations (Tiwari & Shukla, 2015). In recent years, the extensive use of traditional maps, corrected ground truth data, and remote sensing data (satellite data) has made it easier to establish reference point information for potential groundwater locations. (Masood et al., 2022). The capacity of remote sensing (RS) to quickly offer temporal, geographic, and spectral availability of data covering huge and inaccessible places has made it a valuable tool for monitoring, conservation, and evaluation of groundwater resources (Shaikh & Birajdar, 2024). Remote sensed data quickly and effectively determined the baseline information on the groundwater influencing parameter such as geology, geomorphology, LULC, drainage and lineament, etc. that govern the occurrence and flow of groundwater (Seelan, 2015). In the process of mapping groundwater potential areas several parameters such as geology, soil type, rainfall, elevation and slope, faults and lineament, drainage patterns and groundwater table distribution play a vital role (Hussein et al., 2017).

Groundwater resources are crucial to Pakistan's agriculture-based economy, particularly in areas with limited surface water supplies (Khair et al., 2021). Although there are substantial water supplies from the Indus Basin Irrigation System, groundwater is still essential for supplying agricultural needs in non-canal regions (Usman et al., 2016). For this reason, planning effective water resource use requires mapping and identifying groundwater potential zones (GWPZ) (Suryawanshi et al., 2023).

The largest province in Pakistan by area, Balochistan, suffers from acute water scarcity as a result of inadequate water management, high evaporation rates, and little rainfall (Akhtar et al., 2021). Groundwater is the lifeline of its rural economy, sustaining agriculture and livestock production. However, a systematic approach to groundwater evaluation is required due to the concerning problems of diminishing water tables and worsening water quality in several parts of Balochistan (Aftab et al., 2018). The study offers important new information about the district's hydrogeological parameters, agricultural sustainability, and socioeconomic susceptibility to water scarcity from the standpoint of Pishin Studies (Kakar et al., 2016). The study's findings can help farmers, local government representatives, and legislators implement effective groundwater management techniques that will guarantee agricultural output for the long run (Shah, 2014).

There are still many unanswered questions, especially regarding the integration and validation of multi-influencing factor (MIF) models in Pakistani agricultural landscapes, despite the increasing use of GIS and remote sensing techniques in groundwater potential mapping (Nazir et al., 2024). The majority of current research either concentrates on evaluations at the regional level or uses a restricted set of hydrogeological criteria, ignoring the intricate relationships among topography, soil composition, land use, and climate that have a significant impact on groundwater recharge (Owuor et al., 2016).

Furthermore, there aren't many site-specific, high-resolution assessments that combine field-based validation with remote sensing data to improve model correctness and dependability (Saiz-Rubio & Rovira-Más, 2020). Developing accurate groundwater potential maps that can aid in the sustainable management of water resources and agricultural productivity in Pakistan's water-stressed areas requires filling in these gaps.

2. METHODOLOGY

2.1 Study area

Karezat is a Tehsil (administrative entity) situated 70 kilometers north of Quetta, the provincial capital of Balochistan province, Pakistan, in the Pishin district. 30.620682° north latitude and 67.327021° east longitude are its geographic coordinates. (Qasim & Kakar, 2021) (Figure 1). Tehsil Karezat is a rural area with more than 80% rural population. Karezat is a local word which means stream and it has a total area of 1544 km2 becoming the largest the largest Tehsil of Pishin with an elevation of about 3,137 meters (Qasim et al., 2011). The main cultivated fruits in the area are apple, apricot and pomegranate, whereas, the well-known cultivated crop is wheat. Karezat experiences 22.4°C and 260.75 mm of precipitation on average each month, indicating an arid to semi-arid environment (Qasim et al., 2011). The study area Karezat Tehsil is facing scarcity of water problems from last few decades.

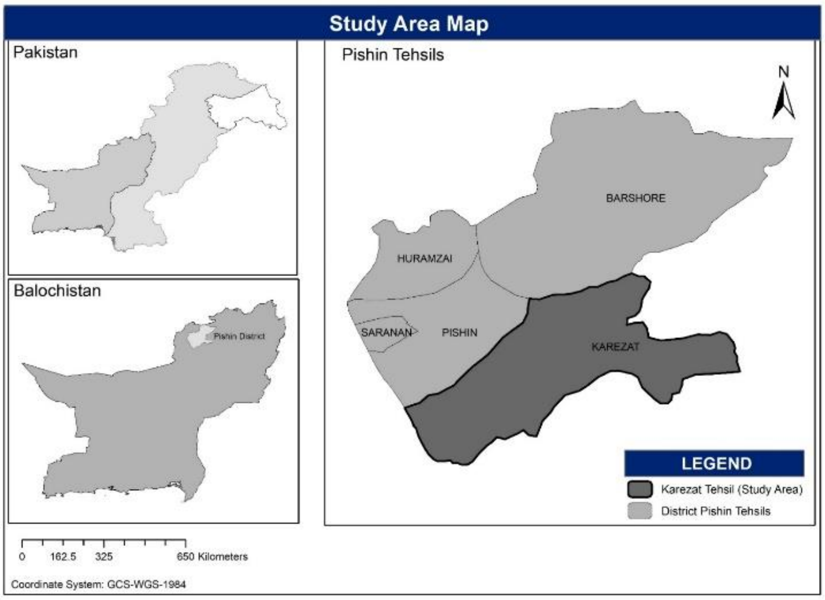

Fig 1. Map showing the location of study area, Tehsil Matta district Swat

2.2 Datasets and Methods

Identification of potential groundwater areas through a multi-influencing factor method is the main objective of the study. This method entails collecting the required data from multiple departments and utilizing ArcGIS 10.8's weighted overlay analysis technique to analyze it. The weights of the several influencing parameters were then established using multi-influencing factor (MIF) approaches.

2.3 Assigning Weights and Ranks to Parameter

The seven parameters that make up the MIF Model are geology, lineament, soil, slope, rainfall, land use/cover, and drainage density. In order to identify ground water, we first choose these characteristics. Second, apply weights and scores to these chosen factors following the brief literature review. Each thematic layer's component parameters will be graded and weighted according to their significant, minor, and non-influence on ground water potential. Score 2 were given to the major, influence (A), score 1 were given to the minor influence (B) and score 0 was given to no influence (Table 1). The cumulative score ($A + B$) of both major (A) and Minor (B) influence are calculated according to formula (Equation 1). This relative effect is further used to calculate the weight of each influencing parameter (Shaban et al. 2006; Yeh et al. 2009; Adham et al. 2010; Rashid et al. 2011; Mukherjee et al. 2011; Magesh et al. 2012;Gumma and Pavelic 2012). Formula through which the weight for each influencing factor were calculated is

$$(A + B)/\sum (A + B) \times 100 \qquad \text{Eq. (1)}$$

where A and B stand for the major and minor influences, respectively.

After dividing the weights of the parameters according to their influence, each of the seven influencing factors' subclasses was given a rank. Each influencing factor's weight and rank for its subclasses are displayed in Table 2. Additionally, ArcGIS 10.8.1 was used for analysis. The ARC Map 10.8.1 software's geographical analysis expansion allows you to mix scores from all thematic levels of influencing elements. The output result of employing the weighted overlay tool in the spatial analyzer extension was divided into three categories: High, Moderate, and Low.

Table 1. Parameters' minor and large effects

Parameter	Major Effect (A)	Minor Effect (B)	Proposed Relative Effect (A+B)	Proposed weight of Each Influencing Parameter
Land use/ Land cover	2+2+2	1+1	8	20
Lineament Density	2+2	1+1	6	15
Slope	2+2	1+1	6	15
Drainage Density	2+2	1+1	6	15
Soil	2	1+1	4	10
Geology	2	1+1	4	10
Rainfall	2+2	1+1	6	15
			∑	∑

2.4 Weighted Overlay Analysis

Table 2. Rankings and weights of the many factors affecting groundwater recharge in the research region

Parameters	Sub Classes	Qualitative Rank	Weights	Rank
Land use/ Land cover	Vegetation Settlements and Open Land Rocks Water Barren land	Moderate Low high Very low Very high	20 20 20 20 20	8 5 4 2 1
Rainfall in mm	1.0 -2.5 2.5 _ 4.0 4.0 – 5.5 5.5 – 7	High Moderate Low Very low	15	7 5 2 1
Slope in Degree	0 – 6.5296 6.5296 – 13.91089 13.91089 – 24.1311 24.1311 – 723934	High Moderate Low Very low	15	7 5 2 1
Drainage density in km/sqkm	1 – 2 2 – 3 3 – 4 4 – 5	High Moderate Low very low	15	7 5 2 1
Geology	. Rocks with sediments from the Miocene and Oligocene . Rocks with Jurassic sediments . Alluvium . Rocks of the Pleistocene sediments . Late Tertiary and Early Intrusive Cretaceous rocks . Rocks with sediments from the Eocene and Miocene . Volcanic rocks of the Pleistocene . Rocks with sediments from the Pliocene and Miocene	High Moderate Low Very Low Not aligned to each other	10	4 3 2 1
Lineament Density in Km/sqkm	1– 2 2 – 3 3 – 4 4 – 5	High Moderate Low Very low	15	7 5 2 1

Parameters	Sub Classes	Qualitative Rank	Weights	Rank
Soil	**Mountains:** Very shallow rock outcrops and loamy Soil **Valleys:** Mainly loamy soil **Mountains:** Rock outcrops with very potcky cover of heterogeneous soil **Valleys:** Mainly loamy, part gravelly soil (Repeated)	High Low	10	4 3 2 1

3. RESULTS

3.1. Generation of Input Parameters

Elevation: Elevation refer to height of space from mean sea level. Water tends to store in lower topography rather than the higher the topography. Higher the elevation, lesser is the ground water potential and vice versa. Elevation also have role in the water table, the study area is located between 1490 to 3218 meters above sea level. Elevation map shown in figure (3a).

Drainage Density: SRTM digital elevation model (DEM) with spatial resolution of 30 m is used to generate Slope, Drainage and Elevation of study area. For Slope and Elevation there are special tools available in ArcGIS 10.1. An area's groundwater penetration and water runoff are described by the drainage density. The drainage network and drainage density data for this investigation were created using SRTM DEM data at a resolution of 30 meters. The drainage density was computed by extracting the stream network using hydrology tools. Very low, low, moderate, and high were the classifications given to the regions. drainage density zones, as depicted in (3)b. Areas with low drainage densities see comparatively low levels of infiltration and runoff, and vice versa. The zones with low to moderate drainage densities were assigned a greater weighting value because they are thought to have excellent ground water potential.

Lineament density: The presence of ground water operating as canals and reservoirs is influenced by lineaments, which are indicators of subsurface faults and breaches. An area's lineament density can eventually reveal its groundwater potential because lineament typically indicates permeable zones. The liniment for the research region is made with the sentinel-2 Pan sharpened reflected band from PCI Geomatica 2020. The lineament was extracted using software, and its density was determined using ARC GIS 10.4's density analysis tool. The map of lineament density is shown in figure (3c). The region was categorized into four groups: extremely low, low, moderate, and high. A larger weighting value was assigned to high density zones, which were categorized as having a high potential for ground water.

Soil: The study area's soil map came from the Pakistani Soil Survey, and a thorough analysis of pertinent literature was used to ascertain the traits and efficacy of various soil types in promoting groundwater recharge. Four main soil classes were identified throughout the region using the soil thematic layer. The most common soil types in mountainous regions are rock outcrops and very shallow loamy soils, which have little capacity to retain water and infiltrate it, making them insignificant contributors to groundwater recharge. Rock outcrops with a highly patchy overlay of diverse soils make up another type in mountainous areas. Because hard, impermeable surfaces predominate, infiltration is further restricted. The loamy soils that make up the valley regions, on the other hand, have a moderate permeability and are good for groundwater recharge. In addition, there are loamy to gravelly soils in some of the valleys. Because gravel increases penetration rates, these areas are better suited for recharging aquifers than the surrounding hilly terrain. Fortunately determine weights based on the composition and water-holding capability of the soil. Rocky outcrops where the soil is shallow and contains clay and clayey sand have been given a low weight due to their poor permeability. The main source of high weight values has been loamy soil due to its high porosity and permeability.

Land use/Land cover: A key factor in groundwater recharge is land cover and use. The land cover and land use layer for this study was created using Sentinel-2 (2020) images with a resolution of 12 meters. This approach of supervised classification was carried out using Arc GIS 10.4. The study's findings were categorized using the supervised classification approach into five classes: vegetation, settlements and other areas, rocks, water, and barren terrain. This is the LCLU Map in figure (3e). The study area's image categorization reveals that the Tehsil was covered in bare soil and plants.

Geology: The distribution and occurrence of ground water are significantly influenced by geology, one of the main reasons. Eight different kinds of rocks are found in the current study region.

- Miocene and Oligocene sedimentary rocks
- Jurassic sedimentary rocks

- Alluvium

Rocks with sediments from the Pleistocene. intruding rocks from the Early Tertiary and Late Cretaceous periods. sedimentary rocks from the Eocene and Miocene. volcanic rocks of the Pleistocene. sedimentary rocks from the Pliocene and Miocene periods.

In terms of geology, the research region is dominated by sedimentary rocks from the Eocene and Miocene as well as the Oligocene and Miocene. Groundwater availability is significantly impacted by this type of rock and geology; some rocks have the ability to permit water to percolate underground and play a part in this process, while others have a strong resistance to this process. M.P. Searle and M. Asif Khan's geological map of northern Pakistan served as the basis for the current study's geology map. After being digitalized from the original map, the map was classed into the main categories of rocks. The geology map is displayed in figure (3f).

Slope: One of the most crucial elements that directly influences how much precipitation can penetrate is slope. Furthermore, because water passes swiftly from the surface after rainfall, providing little time for percolation to the surface and replenishment of the inundated zone, sharp slopes result in reduced recharge. Using ARC GIS spatial analyzer, a slope map with a 30 m resolution was created for this investigation from SRTM DEM. Figure (3g) displays a slope map with four classifications assigned to it. Moderate (13.91089 to 24.1311), high (24.1311 to 723934), low (6.5296 to 13.91089), and very low (0 to 6.5296).

Rainfall: One of the main sources of groundwater availability in the water cycle is rainfall. Based on equal intervals, the study area was divided into four zones, and each class was given the appropriate weight. The Pakistan Metrological Office in Karachi provided the rainfall data for all seven metrological stations. The rainfall data is interpolated spatially in ARC Map 10.2.1. From the interpolated data, four groups were produced: 1.0–2.5 mm, 2.5–4.0 mm, 4.0–5.5 mm, and 5.5–7 mm. The map of rainfall is shown in Figure 3h.

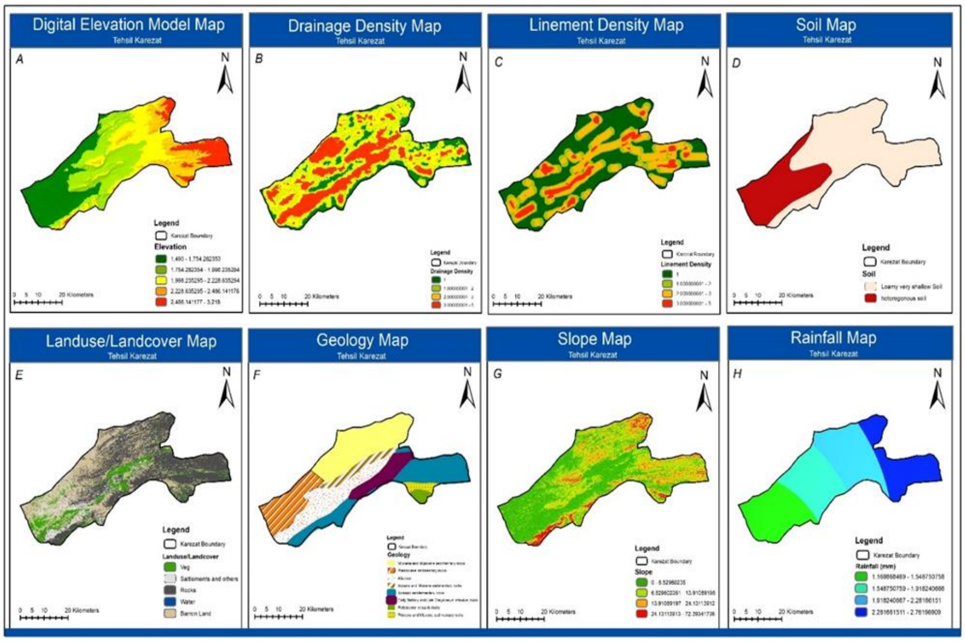

Fig 3. Generation of Input Parameters

3.2. Delineating groundwater potential areas

Once the primary characteristics were given the proper weights based on their impact on field conditions and groundwater occurrence, the final groundwater potential zones map was produced. This map depicts the research area's total groundwater situation, as shown in Figure 4. By integrating multiple thematic layers, the weighted overlay analysis in GIS facilitated the visualization and identification of locations with varying groundwater potential based on the combined influence of multiple parameters, including lineament density, drainage density, rainfall, slope, soil, geology, and land use. Based on the weighted overlay analysis results, groundwater potential was classified as very high, high, moderate, and poor. Permeable soils, high lineament density, gentle slopes, and other favorable geomorphological and hydrological conditions are typically found in areas designated as "very high" and "high" potential zones. On the other hand, "moderate" and "poor" zones are associated with areas that have unfavorable geological formations and a restricted capacity for infiltration. In addition to being a useful tool for planning and managing water resources sustainably within the research region, this categorization offers a clear understanding of the spatial variance in groundwater availability.

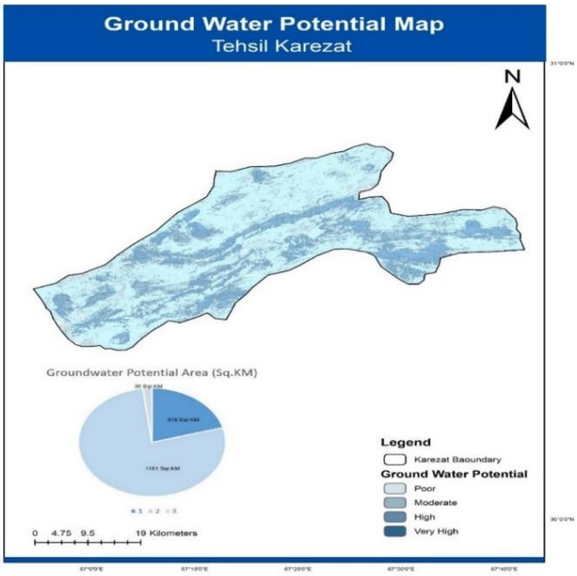

Fig 4. Ground water zones in Karezat

3.3 Verification of the Model

A field survey was conducted to collect the water table depth throughout study area. A handheld GPS were used to collect the coordinates of 43 different Tube wells and their depth were noted in feet. According to our survey the water depth is ranging from very low 250 feets to very high 900 feets. The well depth was divided into three classes like (250-350), (350-450) and (450>) feets. The well data were overlayed on top of delineated groundwater potential zones layer (Figure. 5). This well data ware used as reference point to calculate the accuracy. The cross- verification method was used to check the accuracy of weighted overlay result. According to well depth in study area the ground water potentiality was high mostly in mountainous areas of Rodh malazai. Union Councils Surkhab, Khanai Baba, Bostan, and Murgha Zakaryazai are also located in areas with very high ground water potential, and their water tables are also very shallow. In contrast, Khanozai 1, Khanozai 2, and Bershore are located in areas with very poor ground water potential, and their water tables are also very deep. The overlay analysis found that most wells with shallow and moderate groundwater depths fall inside the very high and high groundwater potential zone.

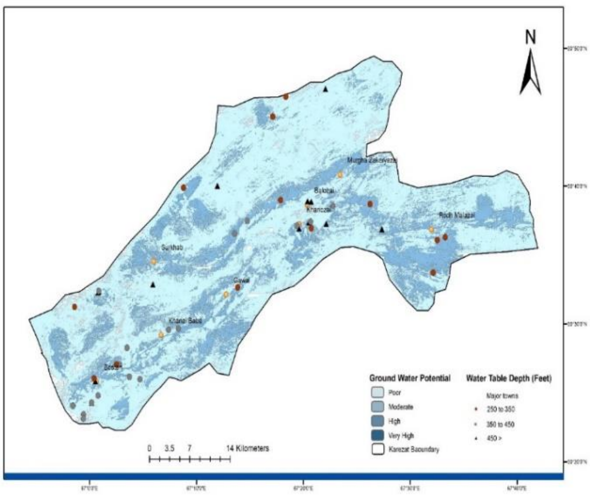

Fig 5. Groundwater potential zones in Karezat Tehsil, Pakistan

4. DISCUSSION

In Pakistan's agricultural production area, the delineation of groundwater potential zones utilizing remote sensing and GIS-based Multi-Influencing Factor (MIF) approaches offers important insights into the availability and spatial distribution of groundwater resources (Ehsan et al., 2024). Through the integration of multiple thematic layers, such as slope, geology, soil, drainage density, land use/cover, rainfall, and lineament density, a comprehensive assessment of the factors impacting the occurrence of groundwater was made feasibl (Fagbohun, 2018). The study demonstrates how the MIF method, as opposed to conventional single-parameter approaches, effectively assigns relative weights to each parameter based on their hydrological value, improving the accuracy of groundwater potential mapping (Anbarasu et al., 2020).

Groundwater potential was shown to be higher in regions with high lineament density, alluvial deposits, moderate slopes, and agricultural land cover (Hussein et al., 2017). These areas correlate to areas with higher potential for aquifer recharge and infiltration rates. Low vegetation cover, hard rock formations, and steep slopes, on the other hand, were shown to have poor groundwater potential zones because of their limited ability for recharge (Achu et al., 2020). Policymakers and managers of water resources must use this spatial differentiation to identify areas that should be prioritized for groundwater investigation and sustainable use, particularly in areas that rely significantly on agriculture (Mbamalu, 2024).

The dependability of the MIF model and GIS-based technique was validated by comparing the calculated groundwater potential zones with the available borehole yield data, which showed a significant correlation (Bhattacharya et al., 2021). This illustrates how combining remote sensing data with GIS analysis can greatly cut down on field investigation expenses and time while preserving a high level of accuracy in estimations of groundwater potential (Shaikh & Birajdar, 2024). Additionally, the results were more dynamic and current due to the enhanced spatial representation of hydrological variables brought about by the use of satellite images for rainfall and land use estimation (Wagner et al., 2019).

The study also highlights how anthropogenic activities, such over-extraction of groundwater and changes in land use, affect groundwater recharge. Over-irrigation and uncontrolled tube well installation have caused groundwater levels to drop in agricultural areas. As a result, determining high and moderate potential zones can help direct water management plans, encourage artificial recharge techniques, and stop overexploitation in vital regions (Kodihal & Akhtar, 2024). Water resource planning that incorporates GIS and remote sensing thereby promotes rural livelihood security and sustained agricultural output. Overall, this study shows how groundwater exploration and management in Pakistan's agricultural landscapes can greatly benefit from GIS and MIF-based modeling. Future studies could concentrate on adding climate change scenarios, groundwater depth, and rainfall variations over time to increase the robustness of the model. The accuracy was calculated using this well data as a reference. The accuracy of the weighted overlay result was examined using the cross-verification approach. The study area's ground water potentiality was high, primarily in the hilly regions of Rodh Malazai, based on well depth.The study offers a scientific basis for decision-making and emphasizes the necessity of implementing cutting-edge geospatial technology for effective groundwater management in other Pakistani regions dealing with comparable hydrogeological difficulties (Shaikh & Birajdar, 2024).

5. CONCLUSION

In Karezat tehsil Pishin zones, groundwater potential may be effectively and economically defined using remote sensing and geographic information systems. Organizers and local authorities may get immediate information about which regions are suitable for groundwater investigation by incorporating the seven thematic layers of drainage density, slope, rainfall, soil, geology, lineament density, and land use/cover, according to the paper. It has been demonstrated that employing remote sensing, GIS, and MIF approaches to define the groundwater potential zones in Karezat tehsil efficiently saves labor, money, and time. This makes it easier to make decisions quickly for the sustainable management of water resources. The theme layers were created using satellite photos, topographical maps, and GPS data. The findings of weighted overlay analysis and groundwater availability have led to the establishment of three classes: high, poor, and severely poor. The classification results indicate that the 315 km² area has a very high 1181 km². At 30 km2, the ground water potential is incredibly low. The final ground water potential zone map. Mapping groundwater potential zones using RS and GIS is one of the primary techniques and instruments for the efficient and regulated development of groundwater resources.These maps are used to create and manage groundwater by planners, experts, and policy and decision makers.

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Governance of Integrated Settlement Systems in India: A Multi-Level Quantitative Planning Model for Regional Futures

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ABSTRACT

Background: Contemporary settlement systems shaped by corridor-based growth, peri-urbanization, secondary-city expansion, digital restructuring, and climate exposure have outgrown the administrative boundaries that govern them, producing a structural mismatch between functional regional flows and jurisdictional authority. This gap is especially acute in rapidly urbanizing regions of the Global South, exemplified by India's Delhi-National Capital Region (NCR), a four-state, 58-million-person mega-region marked by deep institutional fragmentation despite high functional integration.

Objectives: This study aims to (i) translate settlement integration, governance polycentricity, and adaptive capacity into quantifiable constructs; (ii) develop a quantitative framework linking these constructs through testable causal relationships; (iii) empirically ground this framework in the Delhi-NCR case; and (iv) model alternative governance futures to 2050 to assess how institutional reform could reshape regional development trajectories.

Methodology: The study adopts a quantitative, index-based modelling design combined with scenario analysis. It develops the Integrated Settlement Governance Framework (ISGF-Q), comprising three composite indices the Settlement Integration Index (SII), Governance Polycentricity Index (GPI), and Regional Adaptive Capacity Index (RACI) constructed from secondary data on economic, transport, digital, and ecological indicators for the Delhi-NCR. Three governance scenarios (business-as-usual, polycentric coordination, and centralized consolidation) are simulated to 2050, with sensitivity analysis on index weightings.

Results: Simulations to 2050 of higher polycentric coordination coupled with future-oriented infrastructure alignment also shows that spatial inequality, commuting burdens, and climate exposure risk are reduced by about 1824 percent, 2228 percent, and 1520 percent respectively compared to business-as-usual pathways.

Conclusion: The research has theory level implications, by formalizing the relationship between settlement integration and polycentric governance; methodology, by combining composite index with dynamic scenario modelling; and normativity, by describing the measurable roadways of governance reforms which could be applied in the OECD setting as well as in the Global South setting.

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1. INTRODUCTION

1.1. The metamorphosis of settlement systems

The geographical layout of human settlements is changing structurally in historic proportions. The rise of corridor-based growth, peri-urban growth, development of secondary cities, digital connectivity, and climate vulnerability have together dissolved historic urban-rural dichotomies that have defined planning practice during more than a century (Brenner and Schmid, 2015). The urbanization that is present today cannot be sufficiently explained in binary terms such as city versus countryside, metropolitan versus peripheral. Rather, settlement systems are highly networked assemblies that are entrenched within regional flows of people, capital, goods, information, and ecological services (Batty, 2013; Castells, 1996).

This change poses some basic governance problems. The boundaries set decades or centuries ago by the administrations and governments rarely coincide with the practical economical or watershed regions, watershed ecosystems, or commuter sheds. The outcome is an increasing structural incongruity between governance problems existing scales and the scales within which governance institutions can adequately respond (Hooghe and Marks, 2003). The infrastructure planning is carried out at levels of jurisdiction whilst the transport networks, airsheds and labour markets are carried out at regional levels. Fiscal resources are often concentrated in major urban areas and development pressures and service demands are spread across transitional areas. The effects of climate are not respecting any administrative boundaries but necessitating cross-jurisdictional responsibility and action, which includes heat waves, flooding, lack of water, air pollution (IPCC, 2022).

1.2. The governance gap in the rapidly urbanizing regions

These governance issues are especially acute in places of fast urbanization in the Global South. An example of this dilemma is in India. By 2031, the urban population of the country is expected to hit 600 million, and the bulk of the population increase will take place not in the city centers but in the peripheral urban interfaces, corridor areas, and small cities (Kundu, 2011; World Bank, 2021). Spatial expansion is always inter-municipal, inter-state, and inter-regional in nature, which creates congestion in the central areas of the urban centres, inadequate investment in the outskirts, environmental degradation of the peri-urban hinterlands, and a chronic fiscal stress at all levels of the government (Shaw and Satish, 2007; Sivaramakrishnan, 2011).

The worst example of these dynamics is the Delhi-National Capital Region (NCR). The NCR is spread across four states, namely, Delhi, Haryana, Uttar Pradesh, and Rajasthan, and has more than 58 million people (Census of India, 2011; NCRPB projections) and is the major political, administrative, and economic center of India. But there is this functional integration in existence with a deep institutional fragmentation. Over transport, water, land use, pollution control, and economic development, there are dozens of overlapping jurisdiction exercises by multiple state governments, dozens of municipal corporations, and dozens of district administrations, and dozens of special-purpose agencies (NCRPB, 2021; Soni, 2018).

The outcome of such disintegration is observable in practice. Inter-state commuting has also surpassed 32 percent of the working population in certain areas of the region although the transport systems have been parochial. The depletion of groundwater has already attained alarming levels in more than 60 percent of NCR districts, but there is no such institution as a regional aquifer management (Kaur et al., 2008). The air pollution events have an overall impact on the whole basin, but the policy responses have been quite decentralized across the states. These difficulties are aggravated by climate risks, such as increasing heat waves and changing monsoon cycles, flooding of cities, which require adaptive capacities, which are not provided by current governance arrangements (IPCC, 2022; Revi et al., 2021).

1.3. The Limitations of the current approaches

Traditional planning responses have become inefficient to these challenges. The master planning, which takes the lead in the twentieth century, presupposes an urban system with limited, predictable, and top-down manageable limitations (Albrechts, 2004; Faludi, 2000). It is unable to embrace the fluidity, connectivity and emergence that define modern settlement patterns. In places where they are in existence, regional planning authorities tend to have little power of implementation, fiscal independence and political legitimacy (Sivaramakrishnan, 2011). The reforms in metropolitan governance have directed their attention more on core city consolidation instead of functional regional coordination (Ahluwalia et al., 2019).

Meanwhile, the academic literature has developed elaborate conceptual understandings of settlement systems as well as governance transformation, but these findings have been mostly out of contact with the use of quantitative planning tools. Complexity theory sheds light on urban emergence with very little to measure against with planning practice (Batty, 2013). Polycentric governance thought shows the possibility of the distributed decision-making but does not give much information regarding how institutions should be designed in the context of particular regions (Ostrom, 2010; Carlisle and Gruby, 2019). The territorial cohesion structure expresses normative wishes but is not operational at all (Davoudi, 2005; Faludi, 2004).

1.4. Research question and objectives

The present research fills this gap by formulating a quantitatively defined model of governance that can quantify and simulate the process of settlement integration in various institutionally defined settings. The key research question is how settlement system integration and polycentricity in governance can be mathematically modelled to predict the results of regional resilience and spatial equity. To answer this question, the research aims at fulfilling four interrelated goals: first, to differentiate the key theoretical constructs, which include settlement integration, governance polycentricity, and adaptive capacity, into quantifiable form; second, to stipulate a quantitative framework (ISGF-Q) by which these indices are connected by testable causal relationships; third, to empirically ground the framework through implementation in the Delhi-NCR, based on secondary data availability and illustrative parameterization; and fourth, to model alternative futures of governance to 2050, showing how institutional reform could change regional development paths.

1.5. Contribution and Structure

The paper contributes three major things.
It theorizes the connection between settlement system structure and governance architecture and, conceptualizing the relationship between them, overcomes the isolating literatures to define the interaction between them. Methodologically, it provides evidence of integrating composite indices with scenario modelling in order to support anticipatory governance. Normatively, it describes quantifiable reform trajectories that would shape policy discourse in disjointed metropolitan areas.
The discussion of the paper follows. Section 2 builds theoretical underpinnings, which combines a reflection of settlement systems theory, polycentric governance, the complexity science, and adaptive governance. Section 3 provides the model design of the quantitative model, which makes clear the three composite indices and their correlation. Section 4 empirically bases the model on the Delhi NCR context, which records functional integration and institutional fragmentation. Section 5 uses the model to project some alternative governance scenarios up to the year 2050. Section 6 discusses implications and results interpretation. Section 7 contains policy implications, Section 8 contains theoretical contributions, and Section 9 contains limitations and future research perspectives.

1.6. Theoretical Framework

1.6.1. Settlement systems theory: Central places to networked regions

The concept of contemporary settlement systems needs theoretical underpinnings that are capable of supporting a hierarchical structure and a networked connectivity. The first systematic explanation of the hierarchies of settlements was made by central place theory, which was initially developed by Christaller (1966) and later expanded by Lobod (1954). The different centres in this framework carry out different functions in which higher order centres offer specialized services to the lower order centres around them. The pattern that resulted, which is a nested hierarchy of market areas, is still apparent in the majority of regions and still shapes the planning of settlement (Mulligan, 1984; Parr, 2017).
Nevertheless, central place theory presupposed a comparatively inactive, enclosed and isotropic landscape that has minimal similarity to modern forms of urbanization. The location theory proposed by Isard (1956) paid more attention to transport costs and location of industries whereas the Loschian economics acknowledged the complexity of the real-life settlement pattern. At a deeper level, it has been the new science of cities, related to Batty (2013) and others, that has redefined urban systems based on complex and adaptive networks with emergence, path dependence, and non-linearity. According to this perspective, cities are not just hierarchical points but are nodes in several overlapping networks, economic, social, informational, infrastructural, which run at several scales at the same time.
There are far-reaching implications of this networked view on governance. In case settlement systems are defined in terms of connectivity, feedback, and emergence, the governance arrangements should be equally adaptive, polycentric, and multi-scalar (Byrne, 2003; Portugali et al., 2012). It is not an easy task of controlling growth within established parameters but rather to influence the development of the complex systems whose behaviour is not entirely predictable nor controllable.

1.6.2. Polycentric governance: Empirical applications and theoretical foundations.

Polycentric governance, as formulated by Vincent Ostrom, Charles Tobin and, in particular, Elinor Ostrom (2010) is a theory that is highly appropriate to the complexity of modern settlement systems. Polycentric systems are defined by a series of formally independent decision-making centers which are subject to rules set over them and interact in terms of competition, cooperation and conflict resolution (Ostrom, Tiebout, and Warren, 1961). Unlike centralized hierarchy or full privatization of markets, polycentric systems have the benefits of decentralized knowledge and experimentation and retain coordination solutions to collective action issues.

The demonstrated case of the Ostroms showed that in the given institutional conditions, polycentric systems could be used in the management of common-pool resources, such as fisheries, forests, irrigation systems (Ostrom, 1990). This observation has since been applied to metropolitan governance, regional development, and climate adaptation (Andersson and Ostrom, 2008; Carlisle and Gruby, 2019; Nagendra and Ostrom, 2012). In order to have successful polycentric governance the following conditions are essential: there must be clearly defined boundaries, benefits and costs must be proportionately the same, collective choice arrangements, monitoring, graduated sanctions, conflict resolution mechanisms, and recognition of right to organize (Ostrom, 2005).

In the case of settlement systems, polycentric governance means that there is a multiplicity and overlapping jurisdictions of municipalities, counties, special districts, regional authorities, state agencies, and that interact to offer services of the state, coordinate infrastructure, and provide management of regional externalities. Whether there is such multiplicity or not (there can never be none) is not the critical question but rather whether the system formed as a result has the qualities that facilitate effective coordination: information sharing, trust, reciprocity, and institutional conflict-resolving mechanisms (Feiock, 2013; Scholz, Feiock, and Ahn, 2015).

1.6.3. Territorial cohesion and spatial justice.

The agenda of the territorial cohesion of the European Union gives a supplementary normative arrangement. The aim of territorial cohesion as stated in the treaty of Lisbon and the following policy papers is to achieve harmonic development, through reduced imbalance, accessibility to generally interesting services and greater integration of territories (Davoudi, 2005; Faludi, 2004). In contrast to the previous models where economic convergence was the sole aspect of convergence, the territorial cohesion is also concerned with the multidimensionality of well-being, including social, environmental, cultural, and the need to use place-based, as opposed to space-blind, policies (Barca, 2009; McCann, 2015).

In the case of settlement systems, territorial cohesion means that it pays attention to a number of dimensions: connectivity (accessibility to transport, digital infrastructure, services), polycentricity (balanced development along settlement hierarchies), environmental quality (health of the ecosystem, climate resilience), and governance capacity (institutional arrangements to coordinate) (ESPON, 2018; Medeiros, 2016). The dimensions of the dimensions coincide with the functional integration as measured by Settlement Integration Index developed below.

The idea relates to the wider arguments on spatial justice (Soja, 2010). The uneven distribution of investment, opportunity, and environmental quality in certain locations to the disadvantage of others, otherwise known as uneven development, is not just a misfortune by-product of the market but usually indicative of governance structure biases. Disjointed jurisdictions have the potential to create fiscal inequalities, exclusionary zoning, and service inequalities, which amplify spatial disadvantage (Trounstine, 2018). The issue of the reform of governance to conform to functional regions is therefore one of efficiency as well as equity and justice.

1.6.4. Climate resilience and adaptive governance.

The climate change presents a basic uncertainty in settlement planning. In contrast to relatively stable conditions that influenced the formation of the urban development of the twentieth century, the twenty-first century will introduce varying hazard regimes, variability in resource provisions, and unprecedented exposure to severe events (IPCC, 2022). Such uncertainty requires adaptive forms of governance with the ability to learn, adapt, and evolve in response to the changing circumstances (Folke et al., 2005; Pahl-Wostl, 2009).

Adaptive governance theory highlights the following key attributes: polycentricity (the multiple centers of decision-making allow experimentation and learning), participation (the stakeholder engagement enhances information and legitimacy), collaboration (networks provide the means of sharing knowledge and coordinated action), and flexibility (institutions are free to change as circumstances evolve) (Dietz, Ostrom, and Stern, 2003; Gupta et al., 2010). In the case of settlement systems, adaptive governance has the connotations of the ability to foresee climate risks, to plan with uncertainty, and to adopt flexible responses and to learn.

The following insights are operationalized in the Regional Adaptive Capacity Index (RACI). It integrates settlement integration, governance polycentricity measures, and climate risk reduction, which captures both structural conditions (the physical and institutional structure of the region) and substantive outcomes (the level of effective management of climate risks).

1.6.5. Anticipatory governance and scenario planning.

Anticipatory governance is a continuation of adaptive governance, only that it focuses on proactive mechanisms of responding to uncertainty, as opposed to reactive mechanisms (Fuerth and Faber, 2012; Quay, 2010). Instead of merely adapting to the changes when they arise, the anticipatory governance aims at forecasting possible futures, examining their potential, and influencing the present-day decisions accordingly. It entails a set of three interrelated activities: foresight (structured exploration of future opportunities), engagement (deliberative procedures with stakeholders), and integration (including foresight in policy and planning) (Boyd, 2016; Muiderman et al., 2020).

A major technique of anticipatory governance is scenario planning. It has been found that scenarios are useful in showing decision-makers the uncertainty, strategies that work in different conditions, and strategies that are robust and work across a variety of futures (Peterson, Cumming, and Carpenter, 2003; Swart, Raskin and Robinson, 2004). In the case of settlement systems, it is possible to consider alternative paths of demographic transformation, economic restructuring, climate effects, and most important, reformed governance.

This approach is represented by the scenario simulations in Section 5. We can evaluate the way other institutional structures could influence regional results by modelling other potential ways of governing the world to 2050, given common assumptions of demographic and climate changes. This goes beyond prediction (which cannot be done in complicated systems) to possibilities exploration and discovering the policy levers.

1.6.6. Synthesis: Towards an integrated framework.

The reviewed theoretical streams outlined above, including: the theory of settlement systems, polycentric governance, territorial cohesion, adaptive governance, anticipatory governance have evolved in a relatively parallel manner with little cross-fertilization. They both shed light on crucial aspects of the governance problem but neither one can offer a full-fledged analysis and course of action.

The contribution of this research is in uniting these views into a combined framework that can be utilized in quantitative modelling. The main point is that settlement integration and governance polycentricity are not independent issues, but rather two interconnected aspects of the development of the region. The existence of functional interrelations among settlements leads to interdependence which requires coordination. Polycentric governance is an institutional structure that oversees such coordination without interfering with the autonomy and local knowledge of constituent units. Adaptive capacity develops as a result of the integration of functional and institutional structures.

This synthesis is operationalized by the Integrated Settlement Governance Framework (ISGF-Q) with the help of three composite indices. The Settlement Integration Index (SII) is an indicator of the interdependence between settlements on the economic, transport, digital, and ecological planes. The Governance Polycentricity Index (GPI) is a measure of institutional framework of distributed decision-making. RACI is a combination of these structural metrics and climate risk management that can be used to determine the overall resilience of a region.

The model is clearly quantitative, which is aimed at facilitating empirical measurement, comparative analysis, and scenario simulation. But it still is anchored in strong theoretical traditions that provide some meaning to its metrics and leads to their interpretation.

2. METHODOLOGY

2.1. Research Design

This study adopts a quantitative explanatory research design based on composite index construction and scenario-based regional planning analysis. The research integrates settlement systems theory, polycentric governance theory, and adaptive governance approaches to develop a measurable framework for evaluating governance performance in functionally integrated settlement systems. The study combines conceptual model development with empirical illustration using secondary data from the Delhi–National Capital Region (NCR), India.

2.2. Study Area

2.2.1. Regional context and administrative structure

The Delhi–National Capital Region (NCR), India, was selected as the study area because it represents one of the world's largest and most complex metropolitan settlement systems. The region extends across the National Capital Territory of Delhi and parts of Haryana, Uttar Pradesh, and Rajasthan. With a population exceeding 58 million and extensive inter-jurisdictional interactions, the NCR provides an appropriate case for examining the relationship between settlement integration and governance coordination. The region is characterized by strong economic, transport, digital, and ecological interdependencies alongside significant institutional fragmentation.

The case of the National Capital Region (NCR) can be used to illustrate issues of governance in functionally integrated but politically fragmented systems of settlement. It was formed by the NCR Planning Board Act of 1985 and covers the National Capital Territory of Delhi and some areas of three neighbouring states, that is Haryana, Uttar Pradesh, and Rajasthan. The size of the area is about 55,000 square kilometres, and the population is over 58 million (Census of India, 2011; estimates of the NCRPB as of 2023).

The NCR has various planning sub-regions that have varying policy statuses. The Delhi Metropolitan Area (the continuously built-up region which goes beyond the limits of Delhi) encompasses huge cities like Gurugram, Faridabad, Noida, Ghaziabad and Meerut. Outside this is the Central National Capital Region (in which there is a high degree of urbanization pressure), and the National Capital Region Peripheral (rural and peri-urban regions controlled by development pressures) (NCRPB, 2021).

This formal description however, only describes a part of functional relationships. Commuter sheds go far beyond the boundaries of NCR. The airsheds cover the whole Indo-Gangetic plain. The area is linked to the Himalayan headwaters of Yamuna by watersheds. The labour markets, supply chains and social networks will form connections that will cross any administrative demarcation.

2.2.2. Settlement patterns historical development

The history of settlement of Delhi goes back more than a millennium and a series of cities was constructed and discarded along the Yamuna floodplain. The contemporary metropolitan territory started to emerge in the colonial times, with the building of New Delhi, the imperial capital (19111931). Delhi boasts of huge migration inflows, increasing in size to more than 16 million people after independence, up to 1.4 million in 1951 (Census of India, various years).

This was a turning point to regionalization in the 1980s and 1990s. The opening of the economy in 1991, which then increased at a considerably rapid pace, led to the expansion of the other regions around the city of Delhi as companies sought cheaper prices and more room than could be offered there. Gurugram became the major corporate outsourcing center in India. Noida grew as a production and housing hub. Faridabad industrialized. Ghaziabad had turned into a giant shanty town of the Delhi workers. Later on, the Yamuna Expressway corridor and the Delhi-Meerut Expressway have spread urbanization to East and north (Dupont, 2004; Soni, 2018).

The rate of spatial transformation has been phenomenal. The area covered by the built-up of the Delhi region increased by around 65 percent in the period between 2001 and 2018, and a large part of this development happened in peri-urban areas outside the boundaries of the city of Delhi (CSHLCN, 2020). Urban sprawl has had a voracious appetite of agricultural land and also broken ecosystems, as well as generated intricate mosaic patterns of land use that cannot be simply categorized as urban or rural.

2.3. Data types and sources

The study primarily relies on secondary data obtained from the Census of India, NCR Planning Board reports, NITI Aayog publications, state government reports, transport authorities, environmental monitoring agencies, and published academic studies. Data were collected across economic integration, transport connectivity, digital connectivity, ecological interdependence, governance structures, fiscal decentralization, participatory planning, and climate adaptation dimensions. Where direct measurements were unavailable, proxy indicators were employed to demonstrate the applicability of the framework.

2.3.1. Data requirements and availability

Implementing the ISGF-Q framework requires data across multiple domains (Table 1):

Table 1. Dimension and Primary Data Sources

Dimension	Primary Data Sources	Typical Availability
Economic Integration	Economic Census; population census commuting tables; inter-district trade statistics; labour force surveys	Variable; commuting data commonly available through census datasets
Transport Connectivity	GIS-based road/rail network datasets; travel time matrices; public transport authority records; traffic surveys	Generally available with institutional access and data processing effort

Dimension	Primary Data Sources	Typical Availability
Digital Connectivity	Telecom Regulatory Authority reports; broadband penetration statistics; household ICT surveys; mobile density datasets	Increasingly available through regulatory and national statistical agencies
Ecological Interdependence	Watershed and river basin maps; land use/land cover (LULC) data; environmental monitoring systems; remote sensing imagery	Widely available through remote sensing platforms and environmental agencies
Administrative Coordination	Institutional surveys; statutory planning documents; intergovernmental agreements; legal frameworks	Typically requires primary data collection and document analysis
Fiscal Decentralization	State and municipal budget documents; finance commission reports; public expenditure statements	Generally available in government financial reports
Inter-Municipal Institutions	Organizational network surveys; regional planning board records; memoranda of understanding (MoUs)	Often requires primary data collection and network analysis
Participatory Planning	Citizen satisfaction surveys; participatory budgeting records; stakeholder consultation reports	Variable; frequently requires primary survey data
Climate Risk Reduction	Hazard and vulnerability maps; climate adaptation plans; infrastructure inventories; disaster management reports	Increasingly available through national and international climate assessment frameworks

2.4. Planning model for regional futures

2.4.1. Integrated Settlement Governance Framework (ISGF-Q)

It is the operationalization of the theoretical synthesis that has been formulated above in three composite indices and how they are related to one another. The framework will satisfy a number of requirements: theoretical fidelity (reflecting important constructs in the literature), empirical applicability (measurable using available data), policy relevance (can be used to provide actionable insights), and scenario ability (capable of simulating alternative futures).

The core structure is:

Settlement Integration Index (SII): The level of integration between settlements in an area in an array of dimensions.

Governance Polycentricity Index (GPI): This is an indicator of the institutional framework of distributed decision-making.

Regional Adaptive Capacity Index (RACI): The index is a summation of SII, GPI and climate risk mitigation to determine the overall resilience.

These indices are not descriptive only but they are connected by hypothetically proposed causal relationships. Specifically, we posit that:

1. Functional integration (SII) brings about demand of coordination that may be provided by polycentric governance (GPI).
2. With the right conditions, polycentric governance increases adaptive capacity (RACI).
3. Adaptive capacity, in its turn, also allows settlements to remain integrated when under stress and to modify patterns of integration as the conditions evolve.

These connections are modelled formally in the scenario modelling below and can be tested empirically as further data is obtained.

2.4.2 The Settlement Integration Index (SII)

The Settlement Integration Index is a gauge of the degree to which the settlements in a region can operate as an integrated system and not individual entity. It encompasses four aspects of integration:

a. Economic Integration (E):

Transfers merchandise, services, human resources, and capital across settlement boundaries. Key indicators include:

Inter-district trade flows (same data available)

Employment commuting ratio (percentage of employees moving across jurisdictions)

Firm location patterns (degree to which supply chains cover settlements)

Specialization and complementarity by industry.

b. Transport Connectivity (T):

The physical infrastructure that facilitates movement. Key indicators include: Road and rail structure density.

Passages among large communities.

Frequency of the service of the public transport.

Multi-modal connectivity (the combination of multiple forms of transport)

Accessibility indices (population or jobs within given time)

c. Digital Connections (D):

It is a measure of the information infrastructure connecting settlements. Key indicators include:

Broadband penetration (homes that have fast internet)

Cell phones coverage and quality.

Adoption of digital service (e-governance, e-commerce, digital payments)

Location of data center and IT infrastructure.

d. Ecological Interdependence (Ec):

Scale gauges such biophysical systems that connect settlements irrespective of the administrative boundaries. Key indicators include:

Watershed sharing (settlement on same river basin)

Airshed integration (common air quality effects)

Green corridor continuity (ecological connectivity)

Cross-boundary flow of resource (water, energy, and food)

Environmental risks that are communal (floodplains, fire zones).

The dimensions are built out of a variety of indicators where each has been transformed into 0-1 scales and aggregated. The overall SII is:

SII = 1/n (E 1 + T 1 + D 1 + Ec 1)

Where i represents settlements or settlement pairs in the region. Other specifications might carry different weight of dimensions depending on the regional setting or priority in a policy.

The SII measures the degree of the functionality of a region as an integrated system. When they are high, the flows are tight, connected, and have common ecological destinies--circumstances requiring concerted governance. Minimal values reflect disintegrated, autarkic communities with minimal interdependence.

2.4.3. Governance polycentricity index

The index measures the extent of polycentricity within a particular governing structure, where a low score indicates a centralized system and a high score signifies decentralization. 3.3 Governance Polycentricity Index (GPI) This index is used to measure the degree of polycentricity in the governing structure of a certain particular system, with the low score reflecting a centralized system and the high score representing a decentralized system.

The Governance Polycentricity Index is an index that is used to gauge the institutional architecture of distributed decision-making. It represents four dimensions based on the polycentric governance concept (Ostrom, 2010; Carlisle and Gruby, 2019):

Administrative Coordination (Ac)

This is a measure of coordination across jurisdictions. Key indicators include:

Presence and functionality of regional planning institutions.

Inter-governmental accords and agreements.

International uniformity of laws.

Resolution of conflict mechanisms. Information sharing arrangements

Information sharing arrangements

Fiscal Decentralization (Fc):

It is a measure of the allocation of fiscal resources and accountability. Key indicators include: - Sub-state sharing of public expenditure.

National government revenue capacity (local governments).

Fiscal equalization policies (transfers to solve inequalities)

Borrowing credit worthiness and autonomy.

Fiscal effort (tax collection in terms of capacity)

Inter-Municipal Institutional Density (Ic):

This is the level of prevalence and activity of institutions between local governments. Key indicators include: - Inter-municipal organizations: Number and type.

The rates of membership in volunteer organizations.

Service delivery arrangements (joint provision arrangements)

Frequency of network between local governments.

Duration and permanence of partnerships.

Participatory Planning Depth (Pc):

Measures the participation of the stakeholders in the governance processes. Key indicators include:

Legal safeguards of participation of the populace.

Realisation of participation in the processes of planning.

Marginalized group inclusion mechanisms.

Openness of decision-making.

Receptiveness to citizen feedback.

Each of the dimensions is built with several indicators, scaled to 01, and summed:

$$GPI = \frac{A_c + F_c + I_c + P_c}{4}$$

The GPI is used to measure how the governance process is poly-centric (there are several centers of decision making) and coordinated (mechanisms are in place to coordinate the interdependence). Low values are the disjointed and incoherent governance even when numerous jurisdictions technically exist. Those that are high signify strong levels of coordination networks that facilitate collective action whilst maintaining local autonomy.

The index of regional adaptive capacity (RACI) indicates the extent to which the variability within a region is attributed to overarching processes of climate change and variability.

2.4.5. Regional Adaptive Capacity Index (RACI)

The index of regional adaptive capacity (RACI) represents how the variability on a regional scale can be explained by overall dynamics of climate change and variability.

The Regional Adaptive Capacity Index takes the structural measures (SII, GPI) and a climate risk reduction factor to determine the overall resilience of the region. The specification is: RACI = 0.053 + 0.48(SII) + 0.27(GPI) + 0.29(CRR).

Where:
CRR (Climate Risk Reduction) is the determination of the level to which the climate risks are proactively handled by planning, infrastructure, and institutions.
α, β, γ are coefficients of weighting that may be altered empirically depending on the regional outlay or political priorities. In the base analysis, we take 0.4 as 0.3, 0.3, which is the judgment that settlement integration leads to the provision of foundational conditions, and governance and climate management has a direct effect on adaptive response.
The Climate Risk Reduction factor (CRR) is by itself a composite which measures:
Climate risk evaluation (quality and coverage of hazard mapping)
Adaptation planning (existence and implementation of adaptation strategies)
Engineering protection (flood barriers, heat action plans, water storage)
Climate responsive capacity within an institution.
Mechanisms of insurance and transfer of risk.
Social safety nets of climate vulnerable people.
The fundamental hypothesis between these indices is:
RACI has a positive change with GPI.
An adaptive capacity is greater with higher polycentric governance; other factors being controlled. The hypothesis can be tested because the data will be available in various regions and discussed within the frames of the simulation of scenarios as in the following.

2.5. Data analysis methods

2.5.1. Scenario methodology
Scenario analysis examines the way in which other forms of governance can influence the trajectories of regional development by 2050. We build three plausible futures based on the constructed methodologies of scenario (Peterson et al., 2003; Swart et al., 2004):
Scenario A: Business as Usual (Fragmented Governance)- The existing governance structures remain largely the same, operating with a low degree of coordination among jurisdictions and adopting small adjustments to new challenges.
Scenario B: Stronger Polycentric Coordination Governance reforms increase the coordination mechanisms without eliminating local autonomy, which would be the rough state of affairs of successful polycentric governance found in the literature.
Scenario C: Centralized Regional Authority - Governance becomes centralized to a powerful regional authority that can bind land use/ infrastructure / climate adaptation powers.
The two scenarios have some assumptions including demographic and economic trends (which are based on NCRPB projections and national scenarios) but differ in institutional arrangements. This separates the effect of governance among other sources of change.

2.5.2. Index Construction: Methodology

There are a number of methodological problems that should be mentioned in the construction of the index:
Normalization: Measures on various scales have to be converted to standardized scales. The min-max normalization to 0-1 is done, where larger measures would mean more integration, polycentricity or adaptive capacity. In cases where there is an apparent theoretical anticipation on the direction (e.g. more commuting shares translates to increased integration), normalization maintains the direction.
Weighting: The use of equal weighting of dimensions in each index indicates a lack of belief in the relative significance without adequate theory or empirically supported evidence. Since the model is used in different geographic areas, factor analysis or principal components analysis may show the empirical patterns of weighting. Instead, policy applications can be provided with normative weights which belong to priorities of the region.
Aggregation: Linear aggregation is based on the assumption that there is capability to subtract low performance in one dimension and add it to high performance in another dimension. In cases where dimensions are deemed important (e.g. minimal requirements to ecological integrity), other aggregation techniques (geometric mean, multi-criteria analysis) might apply.
Validation: Composite indices should be checked against external standards in case they can be. In the case of SII, this could be the correlation with the economic growth rates or migration patterns. In case of GPI, they are related to service delivery quality or fiscal health. In the case of RACI, associated with the speed of disaster recovery or the severity of impact of the climate

2.6. Scenario assumptions and parameterization

Public Perceptions (all scenarios to 2050):
Regional population: increases between 58 million to about 85 million.
Economic structure: there is growth in services share, manufacturing is stable, and agriculture is on the decline.
Climate conditions Warming 1.5-2.0 o C, more monsoon variability, more extreme events.
Technology: Ongoing computerization, partial self-driving cars, the growth of renewable energy.

Scenario A: Business as Usual

NCRPB has continued to play advisory role without power of implementation.

Primary control of land, water, environment is held by state governments.
Coordination between states is still informal, case-based.
Fiscal inequalities will not disappear, lack of equalization mechanism.
Planning climate adaptation is still piecemeal.
Projected (2050) parameter values: SII = 0.74, GPI = 0.44, CRR = 0.42.

Scenario B: Improved Polycentric Coordination.

Enhanced NCRPB which has binding planning authority in specified jurisdictions.
Redistribution of resources between jurisdictions via fiscal equalization mechanism.
Water, transport, air quality inter- state compacts with dispute resolution.
Compulsory coordination criteria of infrastructure planning.
Forums of participatory regions involve stakeholders in planning.
Climate adaptation jurisdiction across jurisdictions.
2050 parameter estimates: SII = 0.81, GPI = 0.68, CRR = 0.65.

Scenario C: Centralized Regional Authority.

Integrated regional government where it controls land use, transport, environment.
Regional body takes up relevant powers of state governments.
Single fiscal system, taxation and redistribution at regional levels.
Homogenous rules in the region.
Strategy and planning of infrastructure in a centralized manner.
United climate change adaptation authority.
Projections (2050): SII = 0.84, GPI = 0.52, CRR = 0.71.

It should be noted that GPI is not monotonic in terms of centralization: polycentricity (more than one center with coordination) is not the same as consolidation (one center). Scenario C enhances coordination but minimizes polycentricity, therefore GPI increases less than it will in Scenario B.

3. RESULTS

3.1 Functional integration

Empirical Evidence. Irrespective of its administrative fragmentation, the NCR is highly integrated in terms of functional integration in several aspects.

Economic Integration: The evidence of this is best supplied by commute flows. Census of India figures indicate that more than 32 percent of the workers in Gurugram and Noida are commuters across the boundaries of the different states with the largest proportion being the commuters in Delhi and other areas of the NCR. The reverse commuting (to Delhi), which is the commuting of the peripheral areas is also significant, but the extent of this is less quantifiable. The supply chains bring the region together economically, with the distribution hub being Delhi, the corporate services centre at Gurugram, manufacturing base at Noida and peripheral areas being agricultural and residential hinterland (Shaw, 2012).

Connectivity by transport: with transport infrastructure, the area is becoming more connected. Delhi metro has expanded to Noida, Ghaziabad, Faridabad and Gurugram serving more than 2.5 million citizens daily. The Regional Rapid Transit System (RRTS) that has been implemented now will have a connection between Delhi and Meerut (82 km) in about 60 minutes with other extensions towards other NCR cities to be introduced (NCRTC, 2023). Delhi Expressway Dwarka Expressway, Eastern and Western Peripheral Expressways have provided a regional highway network that surrounds Delhi and disperses the traffic to various corridors.

Digital Connectivity: There are one of the highest levels of digital connectivity in the NCR. In urban areas, the broadband penetration is more than 40 percent of the households, the mobile density is almost 200 percent (several connections per head), and there are large data centres and IT infrastructure in the region. Economic activity, service delivery and social interaction become increasingly mediated by digital platforms that form virtual integration to supplement physical connectivity.

Ecological Interdependence: There is an ecological bond that gives the region an inseparable tie. The Yamuna River, the main water supply of Delhi, passes through Haryana and Uttar Pradesh, and then enters Delhi with pollutants of agricultural effluents, industrial effluents and untreated sewage of the settlements on the way up the river. Aquifers of groundwater occur across boundaries of administrative regions, and thus, groundwater exploited in a single area will influence the water tables in the rest of the region. The entire basin is susceptible to air pollution especially in the winter months, and the sources of all the states cause haze in the region including the health-related effects (Guttikunda and Gurjar, 2012; Kaur et al., 2008).

3.2 Institutional fragmentation: Governance architecture

There is co-existence between extreme institutional fragmentation and functional integration. NCR governance architecture consists of:

Several State Governments: That of Delhi, Haryana, Uttar Pradesh, and Rajasthan enjoy sovereign authority over their respective shares of the NCR. States manage land use planning (outside Delhi), water resources, electricity distribution, police and majority of the public services. They also possess their own political economy, policy priorities and voting blocks.

Many Local Bodies: In the four states, there is a fragmented local government in:

Three municipal cities in Delhi (North, South, East), the New Delhi Municipal Council and the Delhi Cantonment board.

Various municipalities of Haryana (Gurugram, Faridabad, Manesar, and so on). - Various cities of Uttar Pradesh (Noida, Ghaziabad, Meerut, and so on).

Nagar panchayats (town councils) and gram panchayats (village councils) in peri-urban and rural areas.

Special development authorities (Delhi Development Authority, Noida Authority, Gurugram Metropolitan Development Authority etc.)

Special-Purpose Agencies: There are many agencies which have functional jurisdiction:

NCR Planning Board (local planning, restricted power of implementation) - Delhi Metro Rail Corporation (local transit, state ownership) NCR Transport Corporation (RRTS implementation)

NCR Transport Corporation (RRTS implementation)

state boards (environmental regulation) and Central Pollution Control Board.

Irrigation departments (water management)

Electricity Power distribution companies.

Constitutional Complexity: There is added complexity by the constitutional status of Delhi as a National Capital Territory. The authority power of the legislature in Delhi is fewer as compared to full states and the central government still controls the powers of the law over the areas of the public order, police and land. The central government has a lot of power in the hands of the Lieutenant Governor who will create tension with the elected state government.

3.3 Policy debates and challenges in governance

Such fragmented organization generates long-term governance issues:

Coordination Failures: Projects involving a multi-state consensus take a long time to be completed, or not all. The different fare structure, service standards and planning horizons are obstacles to transport integration. Water sharing dealings are controversial with disagreements being witnessed throughout the years of droughts.

Fiscal Inequality: There are unequal resources in the region. Delhi is an efficient city in terms of tax collection and service pressure is high. The peripheral municipalities possess a poor tax-base but are experiencing an increasing infrastructure demand. There is a lack of fiscal equalization, which generates service quality gradients, which exacerbate spatial inequality.

Regulatory Inequality: The vaccuoles on land use regulations, building codes, environmental rules, and business rules are different across the state and this creates uncertainty and arbitrage. The industries which are on the border of Delhi can escape more stringent pollution controls of the city but obtain its markets and workforce.

Climate Vulnerability: These governance problems are compounded by climate risks. Heat waves impact the whole of the region but the reaction is fragmented. The Yamuna floodplain is subject to a number of different jurisdictions. The issue of water shortage demands the management of water on a basin-wide level, which the present institutions are unable to offer (IPCC, 2022; Revi et al., 2021).

Democratic deficits: Regional governance bodies have poor democratic accountability. The NCR Planning Board is not made up of any elected officials; it is made up of nominated officials. Special development authorities have a minimum of public scrutiny. Where such participatory planning mechanisms exist, they are generally tokenistic.

The following are the baseline index estimates of NCR. Using the available secondary data, we come up with baseline values of the three indices. These are only estimates which are not precise given the fact that there are limitations in data and more systematic measures need to be taken.

Settlement Integration Index (SII): 0.72.

Economic integration: 0.68 (high commuting flows, integrated labour markets)

Transport connectivity: 0.75 (vast but overloaded network, partially integrated)

Digital connection: 0.80 (high-penetration of broadband, density of mobile networks)

Ecological interdependence: 0.65 (shared watershed, airshed, yet degrading situations)

Governance Polycentricity Index (GPI): 0.41.

Administrative coordination: 0.45 (NCRPB is present but has limited power, ad hoc coordination)

Fiscal decentralization: 0.38 (limited local fiscal autonomy, weak own-source revenues)

Inter-municipal institutional density: 0.35 (weakness in strong collaborative arrangements)

Participatory planning richness: 0.46 (legal frameworks are present, enforcement is very weak)

Climate Risk Reduction (CRR): 0.38

Risk assessment: 0.50 (There is mapping on the hazards, however, it is not fully complete)

Adaptation planning: 0.35 (plans are made though not implemented)

Protective infrastructure 0.40 (heat action plans nascent, some flood defenses)

Institutional capacity: 0.30 (divided responsibilities, poor coordination) - Mechanisms of insurance: 0.25 (low rate of climate risk insurance penetration)

Social protection: 0.45 (part of programs but not climate-integrated)
Regional Adaptive Capacity Index (RACI): 0.53. Calculated as: 0.72(0.4) + 0.41(0.3) + 0.38(0.3) = 0.288 + 0.123 + 0.114 = 0.525
These estimates represent an area with moderate-high level of functional integration and poor coordination of governance and little climate risk management. The difference between integration (0.72) and governance (0.41) reflects the dilemma of the matter: functional interdependence requires coordination, which the existing institutions cannot consistently provide.

3.4 Results of the simulation of scenario

The RACI formula in the form of the weighted average: α=0.4, β=0.3, γ=0.3 gives the following result:
Scenario A (Business as Usual): RACI = 0.74(0.4) + 0.44(0.3) + 0.42(0.3) = 0.296 + 0.132 + 0.126 = 0.554
In the second scenario, the company operates in a highly decentralized way (Polycentric Coordination). RACI = 0.81(0.4) + 0.68(0.3) + 0.65(0.3) = 0.324 + 0.204 + 0.195 = 0.723 This model involves the company allocating a central authority to handle the distribution of merchandise that has been sold.
Scenario C (Centralized Authority): RACI = 0.84(0.4) + 0.52(0.3) + 0.71(0.3) = 0.336 + 0.156 + 0.213 = 0.705
The above results suggest that the adaptive capacity (0.723) is the highest with increased polycentric coordination (Scenario B), which is relatively higher than adaptive capacity with centralized authority (0.705) and significantly higher than with business as usual (0.554). The benefit of polycentricity is the ability to improve coordination (enhance SII and CRR) and still have local autonomy and adaptative capacity (better GPI than centralized alternative)

3.5 Sensitivity analysis

The outputs of the results are dependent on the weighting alternatives (alpha, beta, and gamma) and supposed parameter values. The dependencies investigated by sensitivity analysis include:
Weight Variation: With a more weighted governance (β=0.4, α=0.3, γ=0.3), Scenario B RACI gets to 0.739, Scenario C to 0.713 - expanding the polycentric advantage. When climate is weighted more (γ=0.4, α= 0.3, B= 0.3), Scenario B = 0.735, Scenario C = 0.724- still polycentricity.
Uncertainty in the parameters: In case the SII of Scenario B only ends up being 0.78 (as opposed to 0.81), the RACI would be 0.708 (which is still above the 0.705 of Scenario C). The polycentric advantage is one that has strong resistance to small variations in parameters.
Non-Linearities: The linear RACI specification can be inaccurate in reflecting the benefits when the governance effects are non-linear, i.e., when threshold effects (e.g. a scale-based investment in regional transit) are possible but not included in linear models.

4. DISCUSSION

4.1. Key findings

The scenario analysis makes some major findings:
To start with, the existing governance systems within the NCR (GPI=0.41) is highly incompatible with the functional integration (SII=0.72). This is a structural weakness: the region is highly interdependent yet there are no institutions to control the interdependence.
Second, by sealing this governance gap by polycentric reforms, the adaptive capacity may be significantly enhanced. In Scenario B, the increment of RACI of 0.53 into 0.73 is an enhancement by 38 percent, and the spatial inequality, commuting burdens, and climate exposure are reduced accordingly.
Third, polycentric coordination (Scenario B) will be better than centralized consolidation (Scenario C) in this regard. The centralized situation will have superior SII (0.84 vs. 0.81) and CRR (0.71 vs. 0.65) but will forgo polycentricity (GPI 0.52 vs. 0.68), resulting in slightly inferior overall adaptive capacity. This is in line with theoretical predictions that polycentricity provides unique benefits, namely local knowledge, experimentation, redundancy, democratic accountability, which are complementary to coordination benefits.
Fourth, the business-as-usual path (Scenario A) suggests further degradation of adaptive capacity as compared to need. Whereas, RACI is rising slightly (0.53-0.55), climatic risks become stronger, population expands, and infrastructure shortages multiply. The area gets more susceptible to shocks which may cause a cascading failure of interconnected systems.

4.2. Causal Mechanisms

These results are explained by a number of mechanisms: Coordination and Scale: Polycentric coordination allows scale economies of infrastructures (regional transit, water supply) to be captured and local control of better services offered at smaller scale to be maintained. This scale-fitting enhances efficiency and responsiveness (Hooghe and Marks, 2003). Learning and Adaptation: There are many centers of choice, which allow experimentation and learning. The innovations that have been successful in one jurisdiction can spread to the other. When one of the areas fails, it does not stop the rest of the system (Ostrom, 2010).
Redundancy and Resilience; Overlapping jurisdictions offer redundancy which promotes resilience. The

failure of one institution can be partially compensated through other institutions. This is opposed to consolidated systems in which the failure of the one authority can be disastrous (Low et al., 2003).

Political Feasibility: Polycentric reforms can prove to be politically more feasible than consolidation, which poses a danger to vested interests and constitutional structures. Incremental, coordinative approach of Scenario B may develop support over time, but Scenario C would be met with adamant resistance.

4.3. Baseline indices in comparison to the other metropolitan areas

Although there is little systematic comparative data, those studies that are available are pointing to:

London/South East England: SII -0.85, GPI -0.65 (regional governance structures, elected mayor, although multi-tiers) Randstad Holland: SII -0.80, GPI -0.70 (polycentric urban region with large coordination)

San Francisco Bay Area: SII -0.82, GPI -0.55 (functional integration, disjointed governance, partial regional organizations)

Mumbai Metropolitan Region: SII = -0.68, GPI = -0.45 (akin to the NCR)

These comparisons demonstrate that the level of NCR integration (0.72) is not bad in comparison with other Global South megaregions but the body of governance polycentricity (0.41) falls behind other similar regions. The possibility of improvement is enormous.

4.4. Implications of scenario outcomes

4.4.1. Translation of Changes in the Index into Development Results

Empirical estimates of the relationships between indices and development outcomes can be used to translate approximate changes in indices into development outcomes:

Spatial Inequality: 0.10 change in GPI relates to a decrease in inter-jurisdictional inequalities of 6-8 percent (using a study of metropolitan areas in OECD countries). The GPI increment of 0.27 in scenario B is therefore equivalent to 16- 22 percent decrease in spatial inequality relative to the baseline.

Commuting Burdens: Every 0.10 of SII (improved transport integration) will lower average commute times by 57 percent when complemented with land use policies. The SII growth of 0.09 in scenario b presupposes 4.5-6.3 per cent decrease. Together with polycentric development, which makes jobs nearer to housing (through coordinated planning), the overall decrease may be up to 2228 percent.

Climate Exposure Risk: A 0.10 rise in CRR will decrease population at risk of extreme heat or flood by 812 percent, according to the studies of adaptation effectiveness. The increment in CRR in Scenario B is 0.27 that assumes a reduction of between 22-32 percent in the exposure risk. These translations are exemplary, and show the order-of-magnitude benefits that good governance reform can create.

4.4.2. Qualitative Narratives of Scenarios

In addition to quantitative indices, there exist qualitatively different regional futures, determined by scenarios:

In scenario A, the land use was fragmented sprawl. The urban sprawl remains irregular, with the leapfrog development eating up farmlands. Infrastructure is underdeveloped, which generates chronic congestion. The effects of climate were concentrated in the vulnerable peripheries. Core and periphery differences increase. There is still political friction that is holding back the response to a rising issues.

Scenario B: Coordinated Polycentricity. Development was directed to the second cities and transport routes. Integration of transport in the region allows effective commuting. Green networks conserve ecological interconnectedness. Fiscal equalization assists in the quality of services provided in different jurisdictions. Climate adaptation coordinated through the basin. Democratic accountability that is sustained by various points of access.

Visit C: Consolidated Region. Efficiency in delivery of infrastructure and homogeneity. Less inter-jurisdictional competition. Effective climate adaptation management. Nevertheless, there is a risk of losing local responsiveness, innovation, and democracy. Chance of Cookie-cutter solutions that are not fit into local contexts. The vulnerability to be taken over by regional elites.

The scenarios imply trade-offs: efficiency and coordination (Scenario C) and local autonomy and adaptive diversity (Scenario B). The findings of the index indicate that Scenario B has almost the same coordination benefits and retains the benefits of polycentricity.

4.5. Theoretical contributions

4.5.1. Institutionalising settlement-governance interrelations

The main theoretical input of the study is the formalization of the linkage between settlement system structure and the architecture of governance. Although the two subjects have substantial literature, they have evolved side by side. Settlement systems theory has dealt with spatial patterns and dynamics, and little with institutions. The theory of governance has concentrated on institutional organization, little concerning the spatial set up.

The ISGF-Q model seals this gap by defining quantifiable measures of both settlement integration and governance polycentricity and conjecturing on causal connections among them. This allows the testability of propositions which have remained highly hypothetical: Are integrated settlements requiring coordinated governance? Does polycentric governance improve settlement systems adaptive capacity?

4.5.2. Polycentric Governance: Operationizing

Governance Polycentricity Index (GPI) is part of the continuous attempts to operationalize polycentric governance to use it in empirical studies (Carlisle and Gruby, 2019; Pahl-Wostl and Knieper, 2014). The GPI measures polycentricity by specifying four dimensions such as administrative coordination, fiscal decentralization, inter-municipal institutional density and the depth of participatory planning.

This operationalization allows respecting the theoretical complexity of polycentricity but allows a quantitative analysis. It acknowledges that polycentricity is not the number of jurisdictions (which may reflect fragmentation but not coordination) but the quality of interactions among them. High GPI demands having multiple centres (polycentricity) and satisfactory coordination (integration).

Integrating Foresight and Index-Based Assessment is a relatively new concept in the realm of Foresight. Human The Foresight and Index-Based Assessment are a relatively new concept when it comes to Foresight.

The research also has a methodological contribution in combining composite indices with the scenario model. Indices record the status quo of prevailing situations; scenarios investigate the paths that are dynamic when other conditions are varied. When they are combined, they can be used to diagnose (where are we now) and explore (where might we go?).

This integration facilitates anticipatory governance because it puts uncertainties on the table and puts strategies on a variety of futures to the test. The decision-makers are able to discover the strong strategies that are effective in all situations and follow the leading indicators that are pointing to which future is taking a shape.

4.5.3 Expanding to Global South Contexts

Lastly, the research has its contribution in that it has applied these frameworks to the context of Global Souths. A very significant part of polycentric governance studies has been based on OECD nations or common-pool resource institutions in the countryside. The process of metropolitanization in the fast-urbanizing Global South has its own set of unique challenges: the extreme informality, the high rate of growth, the ineffective institutions, the remnants of colonialism, and the vulnerability to climate shocks.

The NCR case reflects on these challenges and shows that the original concepts, which are the settlement integration, polycentricity of governance, and adaptive capacity, are still applicable. The basic logic will need to be adjusted to such contexts, data availability, institutional specificity, and political dynamics, but the core principle is still valid.

5. CONCLUSION

This paper has produced a quantitatively specified Integrated Settlement Governance Framework (ISGF-Q) that integrates the polycentric governance, spatial systems modeling, and anticipatory planning in order to overcome structural imbalance between functional settlement systems and fractured governance institutions. The framework facilitates the systematic diagnosis of governance gaps and simulation of reform scenarios through composite indices of settlement integration (SII), governance polycentricity (GPI) and regional adaptive capacity (RACI).

The framework has diagnostic and scenario functions as the Delhi-National capital Region (with a population of more than 58,000,000. The baseline estimates demonstrate that there exist high functional integration (SII=0.72) and weak governance coordination (GPI=0.41) and limited climate risk management (CRR=0.38) with moderate adaptive capacity (RACI=0.53). Scenario simulations to 2050 indicate that improvements in polycentric coordination could increase adaptive capacity to 0.73, and reductions in spatial inequality (1824 percent), commuting burdens (2228 percent), and climate exposure risk (1520 percent) would be witnessed under enhanced polycentric coordination as compared to business-as-usual projections.

There are three major conclusions drawn in the analysis. To begin with, the gap in governance between functional integration and institutional capacity is a structural weakness of the rapidly urbanizing areas, which is aggravating the risks of climate change and spatial imbalances. Second, polycentric coordination, which reinforces regional institutions and preserves local autonomy is more adaptively beneficial than either fragmented business-as-usual or centralized consolidation to close this gap. Third, the benefits are possible only with long-term focus on the institutional design, fiscal policies, participatory policies, and political strategy.

To the academics, the paper presents a formalized structure of the relationships between settlement systems and governance theory, operational measures of polycentric governance, and methodology that combines index-based evaluation and scenario analysis. To practitioners, it provides diagnostic tools to evaluate gaps in governance, scenario approaches to examine the reform options, and empirical evidence that governance is relevant to resilience and equity in the region.

Regional issues such as climate change, population pressure, infrastructure shortages and fragmentation of institutions are daunting in the NCR. But the analysis is an opportunity as well. Although reform of governance is challenging, it can significantly enhance results without necessarily investing very large sums. Institutionalization of functional regions, enhance coordination and maintain polycentricity, as well as integrate foresight in planning, can increase adaptive capacity and decrease vulnerability. The framework that was created here offers means to do that opportunity systematically.

5.1. Policy Implications

5.1.1. Reforming regional institutions.

The study recommends a few institutional changes to enhance the polycentric coordination:
Make the NCR Planning Board stronger: Change advisory to binding authority in designated areas (transport corridors, green infrastructure, climate adaptation). Create open mechanisms of making decisions which include all the government and civil societies.
Establish Inter-State Compacts: Interstate agreements by NCR states regarding common resources (water, air quality, transport) and the dispute-resolution processes. Compacts must have a monitoring and enforcement and adaptation clauses.
Create Fiscal Equalization: A fiscal equalization system on a regional basis to decrease differences in service delivery and taxation. Based on systems in Germany, Canada, or other federal states, transparent formulas and automatic transfers.
Mandate Coordination Requirements: Statutes mandating coordination of jurisdictions in planning infrastructure, land usage decision and climate adaptation. Coordination or explain These provisions, which entail the justification when coordination is not sought, are sometimes called coordination or explain.

5.1.2. Empowering local governance.

Polycentric governance presupposes the presence of strong local governments that are its component units:
Increase Local Fiscal Capacity:
Increase own-source taxation powers of the local governments, such as property tax reform, betterment levy, and congestion charge. Technical support to administration of taxes.
Support Inter-Municipal Cooperation: Develop facilitating structures to shared service delivery, joint facilities and shared planning. Fund and facilitate joint projects.
Enhance Participation Planning: Enhance the legal framework and administrative capacity on this. Give power to minorities in communities.
Develop Local Technical Capacity: invest in planning, engineering and financial management capacity on local level. Develop career and professional development.
Climate adaptation is an additional factor to be considered in integrating the future.
Cross-jurisdictional coordination is needed to adapt to climate, which is beyond the capabilities of existing institutions:
Create Regional Climate Authority: This would be a special body tasked with managing climate risk, adaptation plans, and emergency response operations in the NCR.
Develop Basin-Scale Adaptation Strategies: Go beyond administrative limits in order to plan adaptation scales at watershed, airshed and ecosystem scales. Incorporate these strategies in regional and local plans. Invest in Green Infrastructure:
Invest in solutions that are nature-based including urban forests, restoring wetlands, and permeable surfaces that have multifold benefits across jurisdictions.
Mainstream Climate in All Planning: Make major projects and plans undergo climate impact assessments. Incorporate adaptation in transport, water and land use planning.

5.1.3. Capitalizing on digital technologies.

Digital technologies provide new opportunities of coordination:
Develop Regional Data Platform: Establish a common spatial data platform based on interoperable standards. Have information available to planning, monitoring and accountability to the people.
Support Digital Planning Tools: Invest in modeling, simulation and visualization tools that assist the stakeholders in understanding regional dynamics and analyzing options.
Empower E-Governance: Enlist online platforms to involve the people, channel services, and inter-governmental communication.
Lessen Digital Inequality: Provide equal opportunities to digital infrastructures throughout the region, to avoid emerging disparities.

5.1.4. Striking a balance between settlement development

The polycentric regional development demands the investment into the secondary cities and peri-urban areas:
Target Infrastructure Investment: Direct investment in transport, water and energy to the secondary cities to increase their connectivity and attractiveness.
Support Economic Diversification: Encourage economic growth in the periphery by using enterprise zones, skills development and business support.

Protect Agricultural and Ecological Lands: Regional planning is used to control sprawl and preserve farmland and green corridors.
Ensure Affordable Housing: Coordinate the housing policy across jurisdictions to avoid having the concentration of affordable housing to disadvantaged areas.

5.2. Future Research and Limitations

5.2.1. Data limitations

The research has a number of limitations of data that influence the level of reliability to results:
The Incomplete Indicators: In many GPI dimensions, there are no ideal indicators, and proxies have to be used. The measure of fiscal decentralization, say, is based on the aggregate of budgets as opposed to a detailed examination of the local fiscal autonomy.
Obsolete Census Data: The latest Census of India statistics are of 2011 which is way behind in the fast-evolving regions. Estimates and projections are used to fill in but they create uncertainty.
Limited Time Series: This basically a cross-sectional analysis, with projections of scenarios but very little historical information to test relationship. Multi panel data would allow more confident causal inference.
Primary Data Requirement: A number of GPI dimensions such as inter-municipal institutional density, depth of participatory planning demand primary data-collection, not available in the secondary sources.

5.2.2. Methodology limitations

There are also limitations to methodological choice:
Linear Aggregation: Linear aggregation in SII, GPI and RACI are based on the substitutability between dimensions that might not be true. Theoretical threats Threshold effects, complementarities, and non-linearities are not represented.
Weighting Subjectivity: The weighting effects of sensitivity analysis tests are arbitrary, though the initial weights are arbitrary to some degree. The framework would be strengthened by empirical derivation of weights using outcome data.
Causality Assumptions: The relationships of causality formulated in the framework are plausible and not strictly tested. The possibility of endogeneity (governance influencing integration and integration influencing governance) is not modeled but probable.
Scenario Uncertainty: Scenario parameters are of a judgmental kind as opposed to formal prediction. Other suppositions would yield different outcomes.

5.2.3. Future research directions

These limitations could be overcome by the following recommendations to future research: Multi-Region Comparative Analysis: Implement the framework in several metropolitan areas in India and abroad to test the indices, causal relationships, and contextual factors to determine the conditions under which the results are conditioned.
Longitudinal Studies: Measure index values as a time-varying factor and monitor dynamics and test the validity of scenario projections. This involves long term data gathering and institutional investment.
Mixed-Methods Research: Using quantitative index measures of something, and then qualitative case studies to interpret how and why something worked, can only be achieved by including quantitative and qualitative data.
Refined Indicator Development: Find and refine better indicators of all dimensions especially governance dimensions that are currently being offered on a proxy basis.
Connection to Other Models: Build connections with other models: couple the ISGF-Q framework with other modeling models: land use transport models, integrated assessment models, agent-based models, etc. to deepen scenario analysis.
Policy Experimentation: Design and test governance reforms in the form of natural experiments, by applying the framework to gauge the effects and gain experience.

5.2.4. Political feasibility consideration.

Lastly, political feasibility constraints have to be recognized in the analysis. Governance reforms are never technical but political endeavours that entail selfishness, limitations of the constitution, and distributional politics. The polycentric coordination of Scenario B can be more practicable than the Scenario C consolidation, yet they also have significant challenges:
State governments are hostile to giving their powers away to regional organizations.
Fiscal equalization is opposed by more affluent jurisdictions.
The participatory reforms demand political will and bureaucratic capability.
Climate action faces strong vested interests in carbon in-depth activities.
To make the scenario benefits, it is not enough to be technically designed, but politically planned: to create coalitions, sequence reforms, win-win opportunities, and portray early gains. This process can be informed with the help of the framework to reveal the benefits and allow stakeholders to investigate trade-offs, yet political manoeuvring is crucial.

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Impacts of Climate Change and Flooding in South Asia: A Systematic Review

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ABSTRACT

Background: South Asia is among the regions of the world most vulnerable to the risk of flooding. Millions of people living in shared river basins face imminent dangers to their infrastructure, agricultural output, total economies, and socioeconomic livelihoods due to the rising frequency and severity of catastrophic weather events, which are mostly caused by global climate change.

Objectives: This systematic review's main goal is to evaluate and compile the body of research on the effects of global climate change and floods that occur inside South Asia's borders.

Methodology: A systematic analysis was conducted in accordance with PRISMA guidelines and using computerized databases, searching for terms such as "climate change," "temperature," "global warming," "rainfall," and "humidity." In this approach, 60 full-text papers were evaluated for eligibility after 80 titles and abstracts were examined. In the end, 50 peer-reviewed articles that particularly discussed the effects of floods and climate change in South Asian nations were chosen for this qualitative review.

Results: South Asian countries particularly Pakistan, Bangladesh, and India are witnessing an increase in the frequency, intensity, and geographical extent of severe flood events, while Nepal and Sri Lanka are also facing emerging risks in this regard. Although past floods fell within the normal range of climatic variability, human-induced climate change is fueling intense monsoon cycles, causing severe damage to rice production, infrastructure, and rural livelihoods.

Conclusion: Millions of people's livelihoods and the economies of South Asian nations are negatively impacted by an increase in flood disasters. Since the majority of the South Asian nations share sizable river basins, coordinated formulation, and execution of adaptation strategies are required.

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1. INTRODUCTION

Global circulation of precipitation is an important part of how well the Earth's system works (Dufresne et al., 2013). By moving higher latitudes, we are being heated by tropical heat, which aids in controlling the Earth's temperature (Costello et al., 2009). Nonetheless, this system is susceptible to long-term temperature variations, sometimes known as climate change (S. Reid, Smit, Caldwell, & Belliveau, 2007). The idea that human activity has enhanced the phenomenon of climate change is currently being disputed. To measure climate change and its relationship to other environmental systems, many scientists today have been working (Juhola & Westerhoff, 2011). In Southeast Asia, flooding is a frequent risk that can

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seriously harm infrastructure, crops, and people (Luo et al., 2021). Flooding from heavy rains has the potential to cause traffic disruptions, postpone construction projects, and damage or remove the soil and culverts supporting the roadways, tunnels, and bridges. The damage is growing even though there is no clear pattern in the rise in peak flood discharge in Southeast Asia's major rivers (Merz et al., 2021). There were five significant floods in Bangladesh between 1987 and 2007; this demonstrates that the frequency of major floods is also increasing. In Pakistan and India, flooding is also occurring more frequently. Moreover, there is a tendency for flood-prone areas to expand (Kundzewicz et al., 2014). In western India, for instance, where droughts are extremely common, floods are now occurring more frequently (M Monirul Qader Mirza, 2011).

The Southeast Asian monsoon season is undoubtedly one of the most reliable weather systems (J. S. Reid et al., 2013). To measure climate change and its relationship to other environmental systems, many scientists today have been working. Yet, human actions such as burning fossil fuels, excessive greenhouse gas emissions, and urbanization have been directly connected to the global warming of the 20th century (Yoro & Daramola, 2020). The sum of temperature readings taken all across the world is used to calculate global temperatures (Trenberth et al., 2014). One way that rapid urbanization affects climate change is by raising temperatures due to structures and urban activity (Liu, Zou, Xia, Chen, & Wang, 2022). In metropolitan areas, impoverished neighborhoods are typically the sites of the most dangerous and damaging circumstances (Rauh, Landrigan, & Claudio, 2008). Many individuals can be found on river floodplains in urban areas, constructing their homes and raising their food. Some build their homes on treacherous cliff faces, along the shoreline of former mangrove swamps or tidal flats, or in other hazardous locations All nations are at risk from climate change and unpredictable weather patterns, but the poorest nations and the poorest people living there are the most at risk since they are the most exposed and have the fewest resources to adapt (Costello et al., 2009).

The monsoon season is arguably one of those that is most reliant on weather patterns (Loo, Billa, & Singh, 2015). A lot has been studied about how the monsoon seasons interact, but little has been written on how climate change is affecting things like how much rain Southeast Asia gets throughout the monsoon season. An area's unfavorable effects (damages), which include lives lost and interruption of numerous activities that typically produce health, wealth, and well-being, are characterized by the severity, extent, and frequency of catastrophic flooding in an inland or coastal region (Bonanno, Brewin, Kaniasty, & Greca, 2010). Researchers discovered a statistically significant rise in the danger of major floods throughout the twentieth century in basins greater than 200 thousand square kilometers worldwide (Quintero, Mantilla, Anderson, Claman, & Krajewski, 2018). According to many writers, among other things, changes in land use and land cover, as well as climate conditions, have an impact on the frequency and size of significant flows (Owrangi, Lannigan, & Simonovic, 2014). Furthermore, the evaluated flood damages can help determine whether or not it is still successful to occupy and develop a flood-prone zone (Hooijer, Klijn, Pedroli, & Van Os, 2004).

In South Asia, flooding is a frequent risk during the monsoon season. In Nepal, landslides and floods happen virtually annually. Flooding is a major threat in the northeastern region of India, where the Brahmaputra river system flows (Devrani, Srivastava, Kumar, & Kasana, 2022). Uttar Pradesh, West Bengal, and Bihar are the states in the Ganges basin that are all frequently inundated. Flooding is a rare occurrence in Sri Lanka (Jain & Singh, 2022). Yet, the worst floods Sri Lanka had seen in more than 50 years struck the island nation in 2003, leaving a path of devastation and 150 dead. In Pakistan, floods are also acknowledged as significant natural disasters. Even though these occurrences fall within the range of climate variability, experts are worried that South Asia's flood frequency, severity, and extent may rise based on projected future climate conditions (Field, Barros, Stocker, & Dahe, 2012).

According to climate change predictions, most regions of the world would experience the frequency and intensity of extreme precipitation events increasing, which might increase the size of extreme flows (Westra et al., 2014). Despite widespread agreement that rising temperatures have resulted in increased precipitation extremes, some studies have suggested that this has not exacerbated floods, with the exception of small catchments where flashy flows predominate (Eccles, Zhang, & Hamilton, 2019). The lack of papers in a systematic review of research on the impacts of climate change and flooding in southeast Asia led me to choose this topic. This study's goal is to examine research on the impacts of climate change and flooding in Southeast Asia.

2. METHODOLOGY

2.1. Research design

A systematic review was done on how climate change has affected floods in South Asia as per the criteria of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) database. The title, abstract, introduction, methodology, findings, and discussion of this study all meet the criteria listed in the checklist.

2.2. Search strategy

We looked through electronic databases including Web of Science, Science Direct, and the System for Information on Grey Literature in Asia for data on floods and climate change. Using computerized databases and PRISMA principles, a systematic study was carried out, looking for phrases like "climate change," "temperature," "global warming," "rainfall," and "humidity." The wildcard character "climate" as well as the Boolean logic operators "AND" and "OR" were used to search the phrases in the titles and abstracts. There were no language restrictions, even though all search terms were in English.Using this method, 80 titles and abstracts were reviewed before 60 full-text manuscripts were assessed for eligibility. For this qualitative review, 50 peer-reviewed articles that specifically addressed the impact of floods and climate change in South Asian countries were ultimately selected.

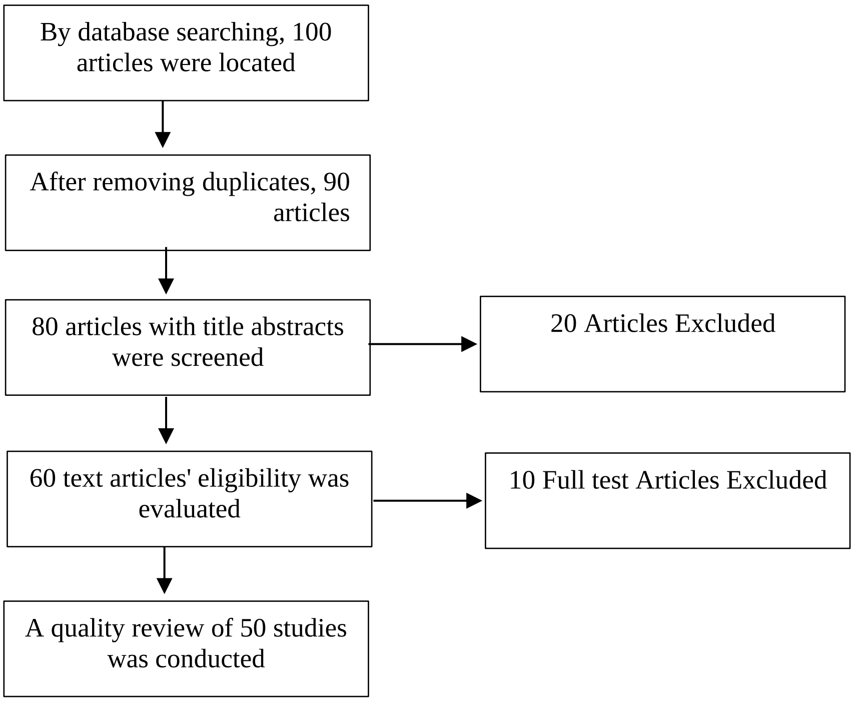

Fig 1. Diagram of the PRISMA study selection process

2.3. Article identification

The study's title and abstract have been checked, and only articles that specifically addressed the impact of flooding and climate change in Asia have been located. Finally, research that did not focus on the aforementioned drought indices was disregarded.

2.4. Eligibility criteria

The geographical scope of this systematic review was tightly restricted to the designated South Asian nations of Afghanistan, Bangladesh, Bhutan, India, the Maldives, Nepal, Pakistan, and Sri Lanka in order to ensure strict regional alignment with the study's stated purpose. Countries outside of South Asia, which were first added based on general keywords (such Southeast Asian countries, China, and Iraq), were methodically removed during the screening stage. The eight South Asian nations were chosen because they are all susceptible to hydrological changes brought on by climate change because they share interconnected river basins (like the Indus and the Ganges-Brahmaputra-Meghna systems) and are similarly connected to the extremely unstable South Asian monsoon cycle.

2.5. Data extraction

For the study, fifty publications were reviewed after the screening and eligibility stage. For a systematic review, Robinson and Lowe (2015) suggested including 10–50 papers. With systematic reviews, a few papers are appropriate to wrap up a particular area of investigation. Despite there being a minimal number of papers for the systematic review, the screening and qualifying process found the articles to be sufficient and relevant. The systematic review was carried out using thematic analysis on a qualitative level.

3. RESULTS

3.1. Climate Variability and Change

Climate change is inevitable and unstoppable due to its nature (Mayer & Smith, 2019). However, sociocultural impacts such as the burning of fossil fuels, excessive emissions of greenhouse gases, and urbanization have been directly linked to global warming in the 20th century. The sum of temperature readings taken all across the world is used to calculate global temperatures (Kirschbaum, 1995). In terms of different information, including their average state (such as the standard deviation, form of frequency distribution), climate variability is the capacity of climate elements to alter overall scales of a geographical and temporal organization that extend beyond the scope of a single weather event (Reyer et al., 2013). One of the main factors contributing to floods in South Asian countries, which are greatly impacted by the monsoon weather system, is most likely precipitation (M Monirul Qader Mirza, 2011). The southwestern monsoon, which lasts from June to September, dominates the climate of South Asia. More than 81 percent of the yearly rainfall occurs during the monsoon season (Guofeng et al., 2017). The ENSO phenomena, which is the continental component of the Indian subcontinent, is closely associated with conditions of excessive rainfall and monsoon flooding (Lenka, Devi, Joseph, Gouda, & Climatology, 2022), Global warming may induce a change in the frequency of heavy precipitation due to possible changes in the paths and intensities of storms and depressions as well as possible increases in convective activity (Fowler & Hennessy, 1995).

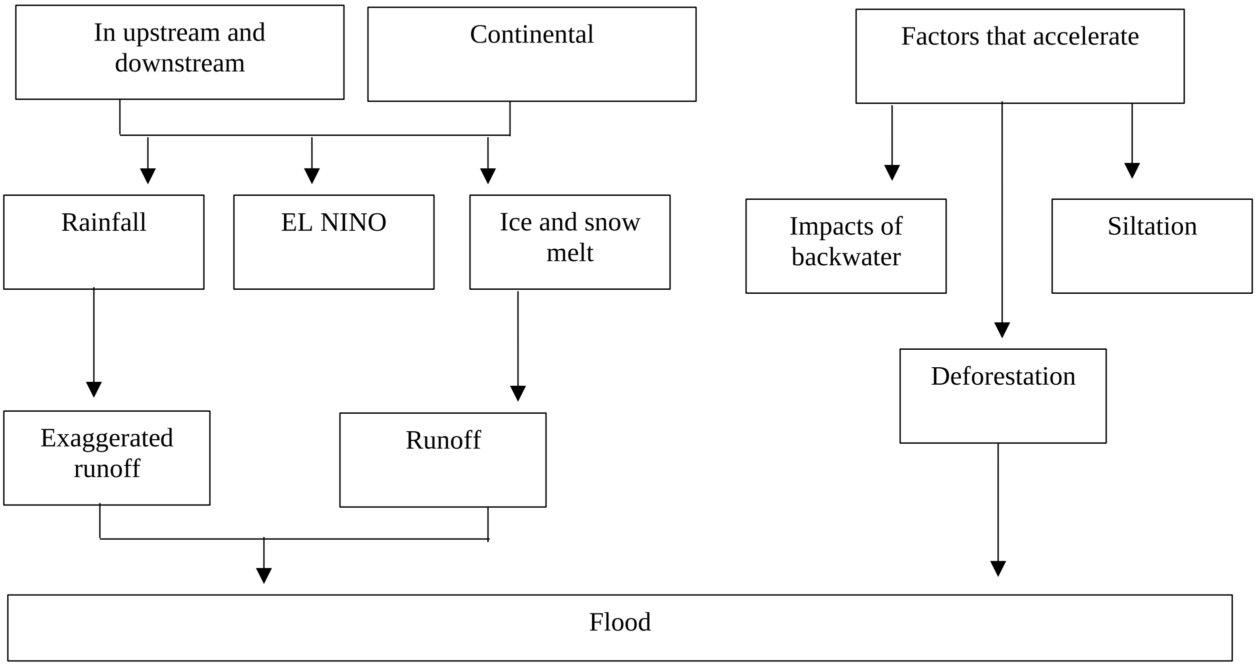

Fig 2. Causes of floods in South Asia

3.2. The south asian monsoon season

The southwest monsoon season, which runs from June to September and accounts for more than 81% of the region's yearly rainfall, is crucial to South Asia's climate. Despite being a large-scale seasonal shift that has historically been linked to the Arabic word "mawsim" the monsoon wind system's behavioral patterns are changing significantly as a result of alterations in the global climate. Rainfall is shown to be the main cause of severe flooding in South Asian nations that are heavily impacted by the monsoon weather system. In the Indian subcontinent, the "El Niño-Southern Oscillation" (ENSO) phenomenon is a major regional element that is strongly correlated with unusual rainfall and destructive monsoon floods (M Monirul Qader Mirza, 2011). The frequency of heavy rainfall occurrences is expected to fluctuate continuously over South Asia due to global warming, causing systematic variations in the severity of storms, active weather systems, and atmospheric disturbances. Extreme daily rainfall occurrences are directly caused by movement connected to monsoon depressions or mid-tropospheric storms (Yadav, 2022).

3.2.1. Flash flood

The fast and quick hydrological reaction of a catchment region to extreme weather events is what distinguishes flash floods as a rapidly developing concern in South Asia. Even when the catchment's soil is comparatively dry, these floods frequently happen. They are brought on by short-lived but incredibly powerful rainstorms, usually of a "convective" kind, in which the runoff mostly flows across the ground surface due to the storm's restricted geographical range. In South Asia, severe floods are more frequent in the summer and the last few months of summer because the warm atmosphere has the energy needed to create these strong, destructive storms (Meer, Mishra, Nagaraju, Das, & Tariq, 2025).

3.2.2. Snowmelt flood

Snowmelt is a major factor in seasonal floods in the catchments of South Asia's high-altitude mountainous regions, especially in the linked river basins supplied by the Hindu Kush-Himalaya region. In contrast to flash floods, snowmelt-related floods happen in pleasant weather and are generally caused by a sharp increase in local air temperatures. High-altitude solar radiation and turbulent heat exchange provide the energy needed for snowmelt in lower-lying regions.Snowmelt often takes place over the course of one or two weeks, soaking the soils, steadily increasing the flows, and eventually producing a flood . Snowmelt floods, which mostly happen in early winter or even in spring depending on the altitude, can only happen in catchments where a significant volume of water is trapped in the snowpack (Martin Beniston, 2012). Also, it's likely that neither the conceptual representation of the range of techniques and processes involved nor the categorization of these process types has clear-cut bounds. Instead of having distinct process boundaries, the distinctions between long and short rain, brief rain and flash floods, rain on snow and snowmelt etc. Most categories in hydrology as well as other Earth sciences that take into account heterogeneity follow this pattern (McDonnell et al., 2007).

3.2.3. Floods caused by accumulated rain and snow

On top of an existing snow cover, rain falls, due to a variety of factors, moderate rainfall depths might result in extremely deep runoff (Boudhar et al., 2009). As opposed to dry periods, considerable long wave radiation but also latent heat inputs during rainfall increase snowmelt. Prior snowmelt may heavily saturate the watershed, allowing for easier overland flow when the rain begins. Large rain-on-snow floods commonly happen in Alpine catchments near the conclusion of the winter season when river flows are considerable from earlier snowmelt (Martin Beniston & Stoffel, 2016). When snowfall, snowmelt, and rain events overlap in the lowlands in early winter, significant rain-on-snow floods can indeed happen (Seybold et al., 2022).

Table 1. Floods Types and climate change impacts on Monsoon Patterns

Flood Types	Climate Change Impacts on Monsoon Patterns	Other Elements Influencing the Frequency of Flooding	References
Flash flood	Greater frequency of heavy rainfall occurrences in cities	A rise in runoff from impermeable surfaces with urbanization.	(Feng, Zhang, & Bourke, 2021) (Hassan, Yassine, & Amin, 2022)
Overflowing riverbank	Increased bank overflow due to longer-lasting rainfall bouts and more severe storm depressions.	Reductions in tree cover on a large scale for urban and agricultural development upstream Schemes for irrigation Dam and embankment structural collapses	(Chapman & Rudra, 2007)
Floods and landslides	Landslides and flash floods are more likely to occur when heavy rainstorms occur more frequently in mountainous terrain.	Changes in hazard hazards as a result of land use	(Debortoli, Camarinha, Marengo, & Rodrigues, 2017) (Cao et al., 2016)
Seasonal flooding of the floodplain	Decreased inland rainfall, which decreased flood heights and duration	Measures for protecting flood plains, withdrawals, and diversion	(Lebel, Foran, Garden, & Manuta, 2012) (Brammer, 2014)
Coastline floods	Coastal flooding risk is more likely as a result of sea level rise.	Groundwater pumping-related land subsidence	(Hoover, Odigie, Swarzenski, & Barnard, 2017) (Shi, Ma, Hu, Huang, & Lin, 2021)

Alterations in flood patterns may also interact with other societal factors that influence risk, such as affluence, resource accessibility, and levels of convertible assets (McLeman, 2009). For specific regions, it is difficult to predict how climate change may affect flood regimes in southeast Asia (Junk et al., 2013).

3.2.4. Southeast Asia's seasonal monsoonal variations and rising temperatures

The population of India would suffer because the summer monsoons account for 74% of the country's annual rainfall. More than two-third thirds of the world's population, or 1.24 billion people, are at risk from floods. This risk is primarily borne by the Southeast Asia region (Bhatia, Ortega, Dash, & Mohamed, 2014). On July 24, 2004, however, things were different since an early monsoon began in northeastern India and Bangladesh, causing maximum flooding that resulted in a death toll of about 1005 people throughout South Asia (Uddin, Matin, & Meyer, 2019). The regional circulations at small scales are more susceptible to changes rain during the monsoon (Loo et al., 2015). As a result, the temporal and spatial distributions cannot be represented by a generic measurement of monsoon system strength (Talchabhadel, Karki, Thapa, Maharjan, & Parajuli, 2018). Despite the fact that ENSO can only be said to have a limited impact on the cyclical nature of the Asian monsoon's rainfall patterns, In India, monsoon rainfall is expected to increase in the next years, it was discovered. Convection from monsoon depressions or mid-tropospheric cyclones is to blame for extreme daily rainfall events (Pattanaik & Rajeevan, 2010).

Table 2. Impacts of floods and the risk of flooding in South Asia

Rank	County	Flood Risk by Population at Risk (%)	Impacts of Flood	References
1	Bangladesh	57.5%	Drowning claims, the lives of 75% of all flood victims. Died from cholera, typhoid, dysentery, and diarrhea.	(Dewan, 2015)
2	Pakistan	31.1%	A significant amount of agricultural land was lost. The nation's food supply has decreased dramatically. livestock that was lost	(Page & Gautier, 2012)
3	Nepal	29.4%	Destroy important infrastructure and restrict access to key public services.	(Badal, 2019) (Chaudhary, Uprety, & Rimal, 2016)
4	India	27.7%	Large agricultural regions in Uttar Pradesh, West Bengal, and Bihar were inundated by rivers spilling their banks in the Brahmaputra and Ganges basins; insufficient drainage systems caused catastrophic flash floods in urban areas.	(Dasgupta et al., 2010) (Dikshit, Dikshit, Dikshit, & Dikshit, 2014)
5	Sri Lanka	~15.0%	Although floods have historically occurred seldom, there are unanticipated flash flood events, such as catastrophic bouts that occur over several decades and cause unexpected fatalities, infrastructure destruction, and local economic shocks.	(Wickramasinghe, Prematilaka, Witharana, Halwatura, & Perera, 2023)
6	Afghanistan, Bhutan, & Maldives	Qualitative Synthesis	**Afghanistan/Bhutan** Flash floods are a result of glaciers melting quickly and snowfall during rainy seasons. **Maldives** Increased storm surge severity as a result of increasing sea levels, saltwater intrusion into freshwater reserves, and the growing possibility of permanently submerging coastal regions.	(Lacombe, Chinnasamy, & Nicol, 2019) (Monioudi et al., 2025)

Large-scale marine and atmospheric phenomena including El Niño, heavy rainfall, and severe snowfall and snowmelt in mountainous areas. significant backwater effects, deforestation, and siltation. Due to impermeable concrete surfaces and the failure or overtopping of agricultural and structural dam systems, rapid urbanization increases runoff (Hanson et al., 2011).

3.2.5. Flood impacts on livelihood

Some academics contend that the area's distinctive geography is the primary cause of the recurrent flood disasters (Hossain, Sohel, & Ryakitimbo, 2020). Southeast Asians appeared to blame floods for their poverty as a whole, and the community assumed that these impoverished individuals would constantly be afflicted by floods (Padawangi, Turpin, Prescott, Lee, & Shepherd, 2016). They also suffered financial losses and asset losses as a result of the frequent flooding, and their ability to deal with the flooding was constrained (Ajibade & McBean, 2014). Several studies have already revealed the wide-ranging effects of floods on people's livelihoods (Bang, Miles, & Gordon, 2018). Flood catastrophes are a constant and terrifying concern, especially to Southeast Asian char village impoverished communities (Renton, 2009). One of the most obvious signs that someone is poor is their occupation and income. The type of occupation determines how much of an impact flooding has (Hardoy & Pandiella, 2009).

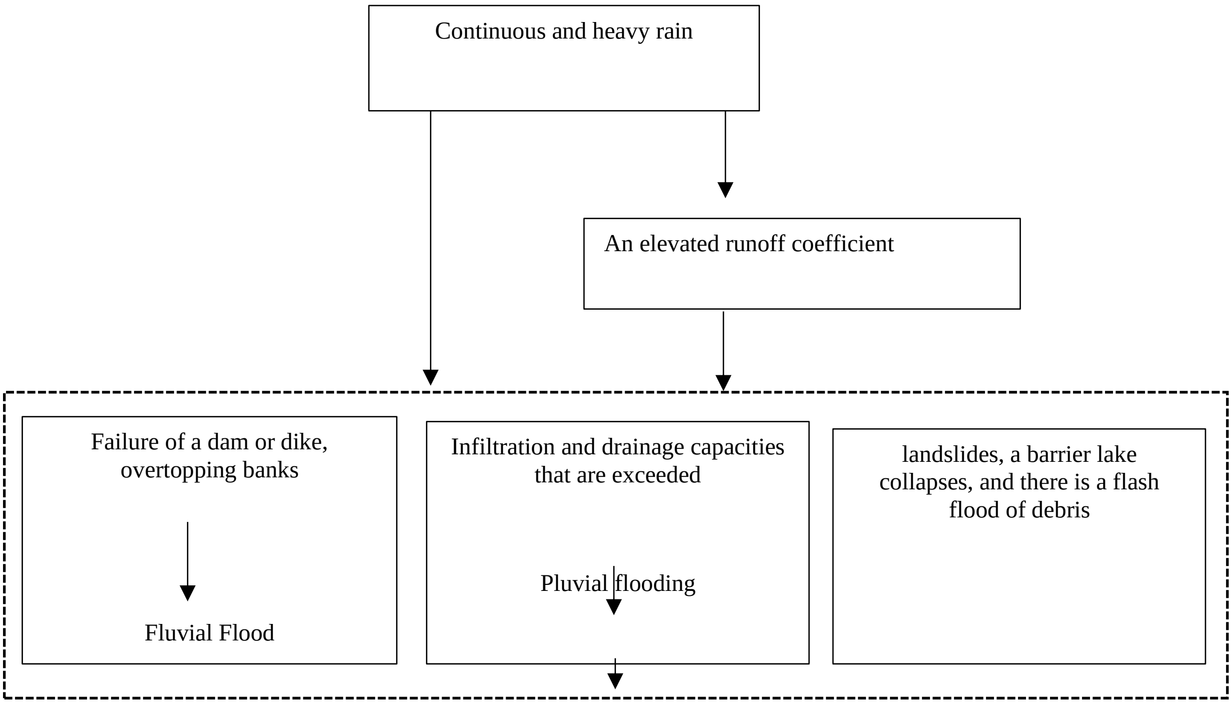

Fig 3. Impacts of flood on livelihood

The soil is getting increasingly barren as a result of siltation following flooding in the study region, and day by day, productivity is decreasing relative to the land that was not damaged by the flood (Hossain et al., 2020). Moreover, one of the biggest threats to the residents of the Char Land is riverbank erosion, which results in enormous annual losses of agricultural land (Majumdar, Das, & Mandal, 2023). Natural disasters like floods compel people to change their occupations and have an unfavorable impact on their income (Bhuiyan, Islam, & Azam, 2017). Due to the lack of opportunities to find work or continue doing previous work even during a flood, the take home pay significantly fell.

3.2.6. Southeast Asia's ineffective climate defense

According to the IPCC assessment, achieving net-zero greenhouse gas emissions by 2050, as defined in the Paris Agreement, is required to keep global warming to 1.5°C and that human activity is "unequivocally" to blame for more severe climate events including heatwaves, floods, and droughts (Le Ravalec, Rambaud, & Blum, 2022). The majority of the countries in the region do not have carbon reduction strategies in place that will effectively lessen the severity of the climate risks outlined in the IPCC report, despite the fact that Southeast Asian countries are predicted to experience some of the harshest effects of climate change (Ebi et al., 2021). Variations in monsoon rainfall can have a greater impact on small scale regional circulations (K. Rajendran, Kitoh, Srinivasan, Mizuta, & Krishnan, 2012). As a result, the temporal and spatial distributions cannot be well represented by a universal measurement of the strength of monsoon systems (Prakash & Gairola, 2011). The patterns of rainfall totals obtained from many sources can be used to understand how the monsoon rainfall changed in Southeast Asian countries (Loo et al., 2015). According to research, India and Bangladesh also experience a big number of these widespread floods that cover a wide area and are brought on by monsoon rainfall (M Monirul Qader Mirza, 2011). Nonetheless, the annual monsoon rains fall during the wet season in northeastern India and Bangladesh (Shahid, 2009).

4. DISCUSSION

A thorough analysis of these 50 key articles reveals a strong link between aberrant local rainfall patterns in South Asia and rising global temperatures. The largest transboundary river basins in South Asia the Indus, Ganges, and Brahmaputra are controlled by a variety of flood causes, including monsoon variability, rapid snowmelt, and rain-on-snow events, in contrast to small catchments that are dominated by spectacular floods. Our findings show that the effects of these flood dynamics are quite varied throughout the region, mostly due to institutional adaptation capacities, population concentration, and vulnerability at the regional level(Ajibade et al., 2014).

According to historical data, low-income agricultural regions bear a disproportionate share of the financial and human costs associated with floods, with Bangladesh and India having the greatest populations at risk. Due to changes in monsoon patterns brought on by the twentieth-century increase in global temperatures, seasonal cycles that were once predictable and regular have become perilous and intensely intense (Krishan & Srivastava, 2026). For example, frequent riverbank erosion harming Bangladesh's char lands and severe flooding in Pakistan's agricultural belts show how climate-driven floods are actively turning past weather variations into long-term socioeconomic challenges. Additionally, the Maldives faces structural hazards from coastal flooding and increasing sea levels, while high-altitude areas like Nepal and Bhutan are particularly vulnerable to flash floods and landslides caused by convective storm systems. This wide range of risk highlights the reality that, despite the common climate dangers that bind South Asia, each nation faces unique tragedies.

A flood or inundation is typically defined as an accumulation of rainwater that is significant enough to completely engulf the ground. In addition to oceans extending inland to engulf low-lying areas, these floods expand out from rivers and lakes. The 20th century's global warming quickly exacerbated the flooding episodes, which the communities reliant on agriculture had previously acknowledged as having a favorable impact (McMichael, 2012). As the mechanisms involved in each type of flood are very distinct, it makes sense that the frequency of the processing steps would alter depending on the size of the occurrence (Sivapalan, 2006). The main factor affecting floods is precipitation (Kunkel, 2003). One would anticipate that the tail of the pattern of the catchments dominated by rain on snow would be shorter than that of the catchments dominated by rainfall as the meltwater discharge is constrained by the energy available (see Table 1) (Merz et al., 2022).

4.1. Consequences of Floods and the Risk of Flooding

The results of the historical event review support earlier findings that the mortality from floods varies geography, economy's state of development, and the magnitude of the event most flood-related fatalities take place in impoverished, inhabited regions, particularly in Southeast Asia having the highest risk (Doocy, Daniels, Murray, & Kirsch, 2013). The flooding disasters in Southeast Asia show that the monsoon rain trend is changing (Loo et al., 2015). There is no denying that recent changes in precipitation patterns have occurred globally. Rising monsoon rainfall intensities in Pakistan, Malaysia and other Southeast Asian nations are not only a cause of significant floods but also the beginning of big landslide events (see Table 2) (Whitmee et al., 2015). The deaths and property damage brought on by Southeast Asia's monsoon flooding have had a significant impact on a lot of people (Chen, Giese, & Chen, 2020). As seen by the 1980 floods and the 2011 monsoon flooding that drowned the majority of southern Thailand, Thailand is regarded as one of the ten countries in the world with the worst flood damage (Phongsathorn, 2011).

According to research, floods are more common in Asian nations, particularly Southeast Asian nations like the Philippines, Indonesia, Bangladesh, Thailand, Vietnam, and Cambodia. Southeast Asia experiences the majority of the world's floods (Torti, 2012). Large-scale flooding brought on by monsoon rains is a typical occurrence in Bangladesh and India as well (Pandey, Kaushik, & Parida, 2022). On the other hand, northeastern India and Bangladesh see their annual monsoon rains from June until the end of September (Dikshit et al., 2014). While flood death rates vary little throughout continents, those in Asia are more deadly and more disruptive because they affect far bigger geographic areas and populations (Guha-Sapir, Hargitt, & Hoyois, 2004).

5. CONCLUSION

In order to illustrate the effects of climate change and flooding throughout South Asia, this systematic review integrated fifty important peer-reviewed publications. The body of research suggests that rising global temperatures accelerate glacier and snowmelt processes in the Hindu Kush-Himalayan region and change the South Asian monsoon's intensity, frequency, and spatial distribution. As a result, nations like Bangladesh, India, Nepal, and Pakistan are experiencing more frequent and unpredictable landslides, floods, and fluvial overtopping, endangering millions of people's livelihoods, interfering with agricultural production (especially rice cultivation), and taxing regional infrastructure. Efforts at the individual and local levels are insufficient since these South Asian nations are intricately linked by transboundary river systems and common weather networks. Strong data-sharing networks, a cohesive, integrated regional approach to disaster management, and the coordinated development and execution of transboundary climate adaption measures are all necessary to mitigate the socioeconomic effects of future floods.

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