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Flood Mapping Using the Sentinel-1 SAR Dataset and Application of the Change Detection Approach Technique (CDAT) to the Google Earth Engine In Sindh Province, Pakistan

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Abstract. Flooding is a natural disaster characterised by overflowing water onto normally dry land, resulting in widespread damage and disruption to communities. Using Geographic Information Systems (GIS) and Remote Sensing (RS) technologies, accurate flood maps can be created. The Change Detection approach was employed using pre-processed Sentinel-1 SAR data. Pre-processing steps, including Thermal-Noise Removal, Radiometric Calibration, and Terrain Correction, were carried out using the Google Earth Engine (GEE) platform. This methodology allows for accurate and reliable analysis of land cover changes and provides valuable information for land management and decision-making processes in the region. The purpose of this study was to estimate the damage caused by flooding. The flood status between 18 August 2022 and 28 August 2022 was analysed. The estimated flood extent based on Sentinel-1 SAR data is almost 759,642 ha. The estimated number of people exposed is almost 663,797, estimated using the Global Human Settlement Layer (2015), with a resolution of about 250 m. Based on a MODIS land cover dataset with a resolution of 500 m, the estimated area of crops damaged is almost 415,450 ha and estimated urban area affected is almost 8435 ha.

Keywords: Remote Sensing, Flood Risk, Indus River Valley, CDAT Algorithms, Flood Inundation Mapping, damage to local communities, endangered cultural heritage.

1. Introduction

Flooding is a recurring and devastating natural disaster that poses significant challenges for the province of Sindh, Pakistan (Memon, 2020). Located in a region prone to monsoonal rainfall and bordered by major rivers, including the Indus River, Sindh experiences frequent floods that have severe impacts on its population and infrastructure (Ali et al., 2020). The vulnerability of Sindh to flooding is influenced by a combination of factors, including climate change, deforestation, rapid urbanization, and inadequate infrastructure (Ashraf et al., 2023).

Climate change plays a crucial role in exacerbating the frequency and intensity of flooding events in Sindh (Naeem et al., 2021). Rising temperatures lead to increased evaporation and moisture content in the atmosphere, resulting in more intense rainfall during the monsoon season (Munir et al., 2022). These extreme precipitation events overload the capacity of the rivers and drainage systems, leading to widespread flooding (Munawar et al., 2022). Moreover, climate change-induced sea-level rise further elevates the risk of coastal flooding in the coastal areas of Sindh (Munawar et al., 2023).

Deforestation, especially in the upstream regions of the Indus River basin, contributes to increased runoff and sedimentation, further exacerbating the flooding risk in Sindh (Otto et al., 2023). Rapid urbanization and encroachments on natural floodplains disrupt the natural drainage patterns and reduce the capacity of the land to absorb and store water, increasing the vulnerability of urban areas to flooding (Otto et al., 2023).

The inadequate infrastructure and poor management of water resources in Sindh also contribute to the severity of flooding (Rana & Routray, 2018). Outdated and poorly maintained irrigation and drainage systems fail to effectively manage excess water, leading to widespread inundation of agricultural lands and urban areas (Hussain et al., 2020). Additionally, the lack of early warning systems and proper flood forecasting mechanisms hampers timely evacuation and preparedness efforts, exacerbating the impact of flooding on vulnerable communities (Khan et al., 2021). The agricultural sector, a significant source of livelihood for the population, suffers from crop losses and soil degradation due to prolonged inundation and sediment deposition (Eimoi, 2020). Furthermore, the spread of waterborne diseases, such as cholera and malaria, becomes a serious health concern in the aftermath of flooding (Hasan et al., 2017). To address the challenges posed by flooding in Sindh, comprehensive flood management strategies and sustainable adaptation measures are imperative. This includes investment in robust infrastructure, such as improved drainage systems and flood embankments, as well as the implementation of effective early warning systems and community-based disaster preparedness initiatives (Twele et al., 2016). Furthermore, promoting afforestation and reforestation efforts, along with the conservation of natural floodplains, can help mitigate the impacts of flooding by enhancing water retention and reducing soil erosion (Uddin et al., 2019).

Flooding events in Pakistan often result from the combination of heavy monsoon rains and inadequate water management, leading to the overflow of riverbanks and drainage systems (Bhatti et al., 2020). The impacts of flooding in Pakistan are multifaceted, affecting infrastructure, agriculture, public health, and the overall economy (Otto et al., 2023). Infrastructure damage caused by flooding in Pakistan includes the destruction of roads, bridges, and buildings, disrupting transportation networks and hindering relief efforts agriculture, a critical sector in Pakistan, is severely impacted by flooding, with loss of crops, soil erosion, and water contamination affecting farmers' livelihoods (Mahmood & Rahman, 2019).

The primary objective of this research is to conduct a comprehensive analysis of flooding, encompassing various dimensions. Additionally, it seeks to evaluate the impact of flooding on cropland, and assessing the damage to crops (Soomro et al., 2023). The research extends its focus to the affected population, investigating social and economic repercussions, including displacement, property damage, and potential health risks. Moreover, the study delves into the effects of flooding on built-up areas, scrutinizing urban and suburban infrastructure damage and evaluating the efficacy of existing flood control measures (Anis et al., 2023).

The economic impact of flooding in Pakistan is significant, with damage to infrastructure, loss of agricultural productivity, and increased public spending on relief and recovery (Tariq et al., 2020). Efforts to manage flooding in Pakistan include the establishment of early warning systems, improved flood forecasting, and the construction of flood protection structures (Nanditha et al., 2023). Integrated flood management strategies that combine structural measures, such as embankments and reservoirs (Tariq et al., 2021). Climate change is expected to exacerbate the frequency and intensity of flooding in Pakistan, necessitating adaptive measures and long-term planning. Community participation and engagement in flood risk management are crucial for enhancing resilience and reducing vulnerability to flooding in Pakistan (Tariq et al., 2021). Collaboration between government agencies, NGOs, and international organizations is essential for effective flood management and the provision of timely relief and assistance to affected communities. Intense or prolonged rainfall is one of the primary causes of floods (Mahmood et al., 2019). When rainfall exceeds the soil's infiltration capacity or when it occurs in areas with impermeable surfaces, such as urban areas, the excess water flows overland and accumulates in low-lying areas, resulting in flooding (Shaikh et al., 2023).

They can cause loss of life and injury, damage infrastructure and homes, displace communities, and disrupt essential services such as transportation, water supply, and electricity (Michel et al., 2020). Floods play a vital role in shaping ecosystems, but excessive flooding can have adverse effects on the environment (Li et al., 2018). They can erode soil, degrade water quality through sedimentation and pollutant transport, and destroy habitats, leading to a loss of biodiversity (Nyumba et al., 2021). Building infrastructure to manage and control floods is another approach (Huang & Jin, 2020). These measures include constructing dams, levees, flood walls, and stormwater drainage systems (Samsuri et al., 2018). The primary aim of this research is to analyze the extent of flooding, assess its impact on cropland, investigate its effects on the affected population, and also examine how built-up areas are affected.

2. Study Area

Sindh, a province located in the southeastern region of Pakistan, is a study area that offers a diverse range of academic opportunities and a rich cultural heritage. Home to bustling cities, historical landmarks, and renowned educational institutions, Sindh is an ideal destination for students seeking both academic excellence and an immersive cultural experience. This article aims to highlight the key aspects of Sindh as a study area, including its educational institutions, cultural significance, and unique features that make it an attractive choice for students. Sindh boasts several prestigious educational institutions, both public and private, offering a wide range of programs across various disciplines. The province is home to renowned universities such as the University of Sindh, Mehran University of Engineering and Technology, and the Institute of Business Administration, among others. These institutions have a reputation for academic excellence, research opportunities, and quality faculty. Whether it's engineering, medicine, business, or social sciences, students can find a program that aligns with their academic interests and career goals in Sindh.

Sindh has a rich cultural heritage that dates back centuries. The province is known for its historical landmarks, ancient civilizations, and traditional arts and crafts. The city of Mohenjo-Daro, a UNESCO World Heritage site, provides a glimpse into the Indus Valley Civilization, one of the oldest urban settlements in the world. Students studying archaeology, history, or anthropology can explore this ancient civilization and gain hands-on experience in excavations and preservation efforts. Furthermore, Sindh is famous for its Sufi heritage and shrine culture. The tombs of Sufi saints, such as Shah Abdul Latif Bhittai and Lal Shahbaz Qalandar, attract devotees from around the world and offer a unique opportunity for students to delve into the mystical traditions of Sufism. The province also hosts vibrant cultural festivals, such as the Sindhi Cultural Festival and Thar Festival, where students can experience the vibrant traditions, music, and cuisine of the region.

Sindh's geographical diversity provides unique opportunities for academic exploration. The province encompasses the coastal areas of the Arabian Sea, the fertile plains of the Indus River, and the desert landscapes of Thar. Students interested in environmental sciences, marine biology, or agriculture can study the diverse ecosystems and gain practical knowledge through fieldwork and research projects. Additionally, Sindh is a melting pot of cultures, languages, and ethnicities. The province is home to the Sindhi, Baloch, and Muhajir communities, among others, creating a multicultural environment that fosters inclusivity and cross-cultural learning. Students can engage with the local communities, learn regional languages, and immerse themselves in the vibrant traditions and customs of Sindh. Sindh also offers various recreational activities for students to unwind after their studies. The coastal areas provide opportunities for water sports, while the Thar Desert offers unique experiences such as camel safaris and stargazing (as shown in Figure 1). Students can also explore the bustling markets, taste the delectable Sindhi cuisine, and shop for traditional handicrafts and textiles.

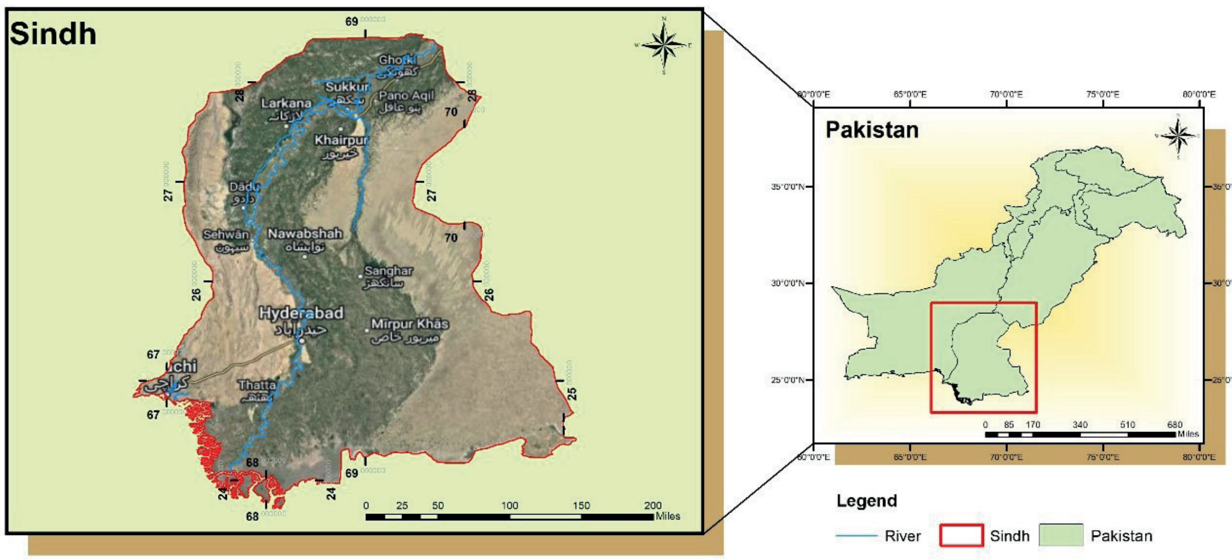

Figure 1. Study Area Map

3. Methodology

In this research use Change Detection Algorithm for Flood Mapping. It is a specific algorithm or methodology used to identify and differentiate flooded areas from non-flooded areas in remote sensing imagery. The CDAT algorithm analyzes changes in image pixel values or other relevant parameters between pre-flood and post-flood images to detect and delineate the extent of flooding. The algorithm applies a specific threshold value or set of criteria to determine which areas have experienced a significant change due to flooding. By comparing the pre-flood and post-flood images, the algorithm identifies areas where the pixel values or other selected parameters exceed the predefined threshold, indicating the presence of water and the extent of the flood event. The CDAT algorithm plays a crucial role in flood mapping as it helps automate the process of identifying and mapping flooded areas using remote sensing data. Its application aids in efficient and accurate assessment of the extent of flood events, supporting disaster response and management efforts.

Firstly, acquire the necessary satellite imagery for the pre-flood and post-flood periods, including optical and SAR data. Import the imagery into Google Earth Engine and preprocess it by performing tasks such as atmospheric correction and image registration to ensure accuracy. Apply the CDAT algorithm to detect and map flood-affected areas, using techniques like thresholding (Fig. 2).

Image Differencing:

$$CD = Postflood\ image - Preflood\ image$$

Thresholding:

$$Flooded\ areas = (CD > threshold)$$

Here's an equation that represents the calculation of flood extent:

$$Flooded\ Area = \Sigma(flooded\_pixel\_area) / 10000$$

The "Flooded Area" represents the total area affected by the flood.

The symbol "Σ" denotes summation, indicating that we sum up the flooded pixel areas.

The "flooded_pixel_area" represents the area of each flooded pixel in square meters.

The division by 10,000 is performed to convert the area from square meters to hectares, as indicated in the code (divide by 10,000).

Adjust the Start-Date and End-Date variables according to the specific date range you are interested in.

The code filters the Sentinel-1 GRD collection based on the defined area of interest, date range, polarization (e.g., VV),

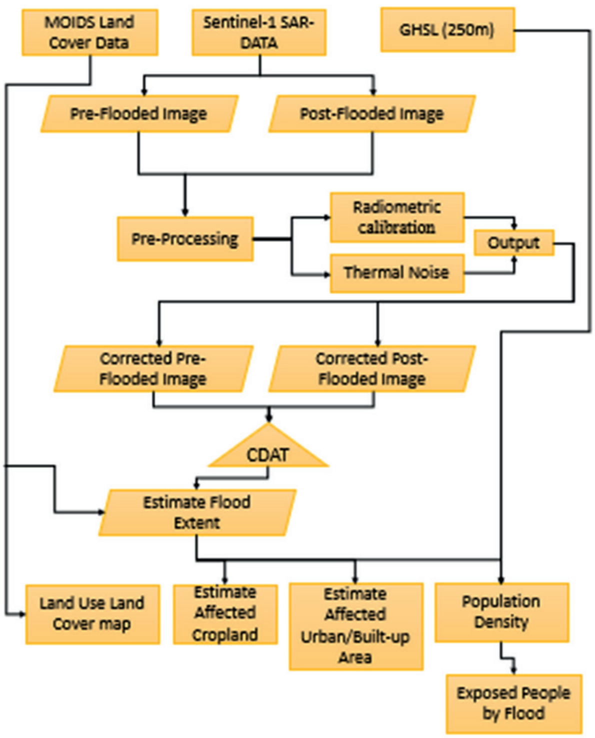

Figure 2. Flowchart of Methodology

instrument mode (e.g., IW), and orbit pass (e.g., descending). You can modify these parameters as needed.

After filtering, you can proceed with further processing, analysis, or visualization using the filtered collection. Creating a mosaic of selected tiles and clipping it to the study area, you obtain a single image that covers the desired region of interest, allowing for more focused analysis and interpretation within that specific area. By incorporating the JRC layer on surface water seasonality and applying a threshold to define "permanent" water, you can effectively mask flood pixels in areas that have water present for more than a certain number of months each year. This approach helps to differentiate temporary flood events from areas with persistent water bodies. Apply the mask to the flood pixels. Use the binary mask created in the previous step to mask out flood pixels in areas classified as "permanent" water. This will ensure that only non-permanent water or land areas are considered as potential flood pixels. Mask out areas with more than 5 percent slope using a Digital Elevation Model. Load JRC Global Human Settlement Population Density layer and create a raster showing exposed population only using the resampled flood layer. We are utilizing the MODIS/006/MCD12Q1 dataset, which offers valuable insights into global land cover dynamics. This dataset consists of annual land cover maps derived from observations captured by the MODIS satellite. The MODIS/006/MCD12Q1 dataset employs a hierarchical land cover classification system known as the International Geosphere-Biosphere Program (IGBP) classification system, providing information on the dominant land cover types within 500-meter pixels. We are using same MODIS product for the calculation of affected urban are we extract the urban class from MODIS dataset.

4. Results

Comparing Sentinel-1 SAR images before and after a flood can provide valuable insights into the changes that occurred during and after the event. The pre-flood image, captured between July 20, 2022 to July 27, 2022, serves as a baseline for understanding the normal landscape and water bodies' configuration. This image can reveal the extent of vegetation cover, urban areas, and the water bodies' pre-flood boundaries. In contrast, the post-flood image, taken between August 20, 2022 to August 30, 2022, captures the aftermath of the flood (as shown in Figure 3). It enables analysts to assess the impact on the landscape, identify the areas that experienced inundation, and measure the extent of waterlogged regions. By comparing the pre- and post-flood images, it is possible to observe changes in water levels, detect new water channels or temporary rivers, and assess the alteration in land cover due to the flood's effects. The Sentinel-1 SAR images provide valuable information through their ability to penetrate clouds and capture radar reflections from the Earth's surface. This enables the detection of flood-induced changes even in areas with persistent cloud cover.

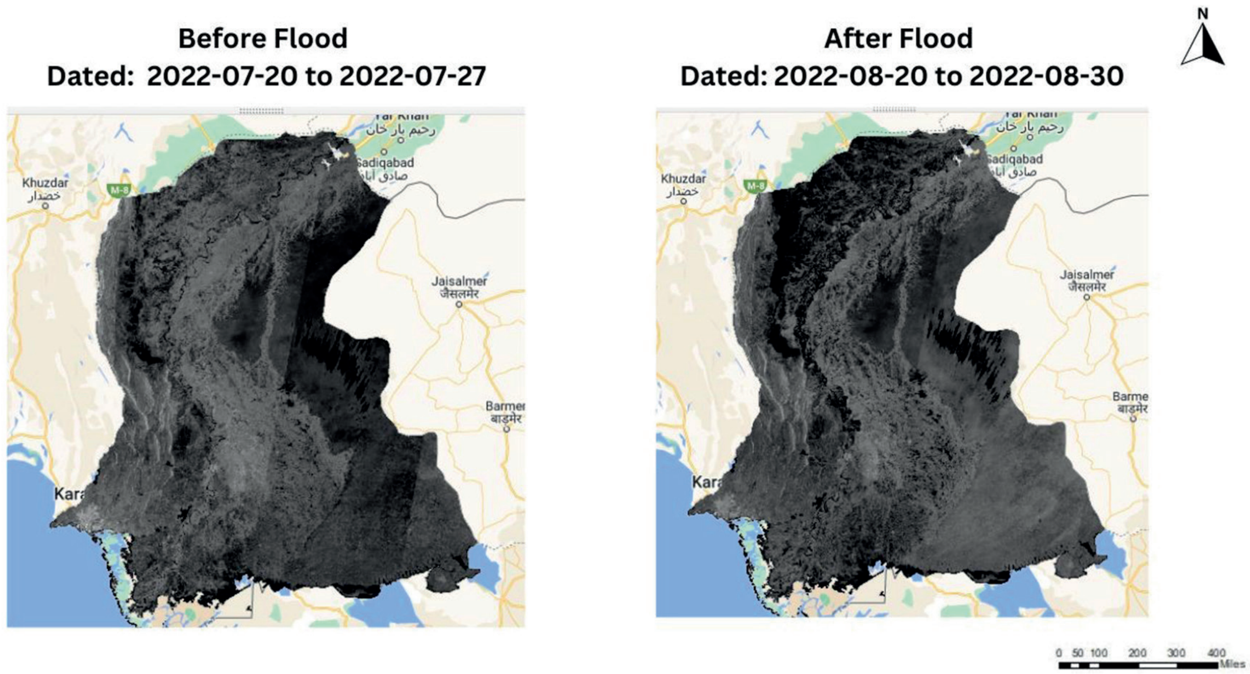

Figure 3. Before and After Flood of Satellite Imagery

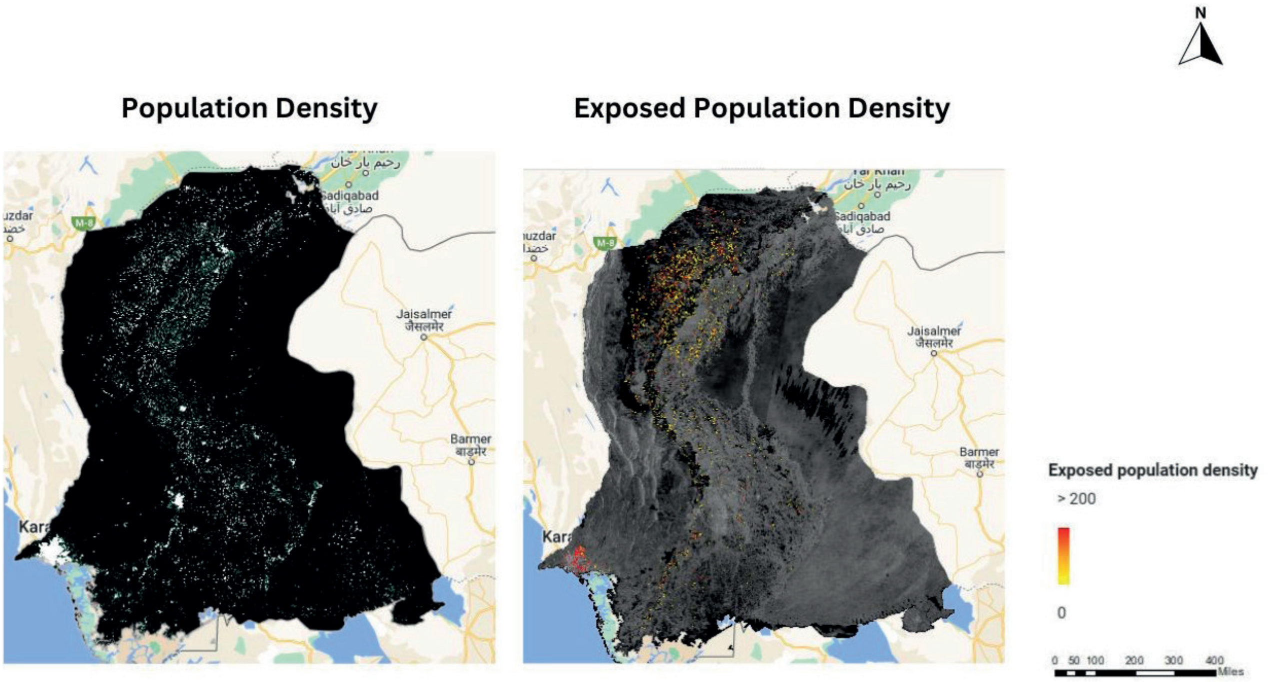

Figure 4. Population Density and Exposed Population Density Maps

Population density refers to the number of people living in a specific area, typically measured as the number of individuals per square kilometer. Exposed population density, on the other hand, represents the population that are exposed by flooding (Fig. 4). To visualize population density and exposed population density using a color ramp from 0 to greater than 200, we can use a graduated color scheme where lower densities are assigned lighter colors and higher densities are assigned darker colors. Decision-makers can identify areas with high population densities and a high risk of flooding, enabling them to prioritize resources for preparedness, response, and mitigation measures. By understanding the exposed population density, authorities can also focus on implementing appropriate measures to protect vulnerable communities and minimize the potential impacts of floods.

The difference layer generated by subtracting the pre-flood Sentinel-1 SAR image from the post-flood image provides a visual representation of the changes that occurred due to the flood. SAR data captures the backscattered radar signals, allowing us to analyze the alterations in the landscape and water bodies. In the difference layer, areas depicted in positive values indicate an increase in radar backscatter intensity, suggesting the presence of water bodies or wetter soil conditions compared to the pre-flood state. These regions might represent newly formed or expanded water bodies, such as flooded areas, temporary rivers, or inundated fields. Conversely, areas shown in negative values suggest a decrease in radar backscatter intensity, which may indicate changes in land cover, such as loss of vegetation or infrastructure. These regions could represent areas that have experienced erosion, vegetation damage, or changes in surface roughness due to the flood (Fig. 5).

Analyzing the SAR data in the difference layer helps to quantify and visualize the extent of flood-induced changes, providing valuable information for flood mapping, damage assessment, and recovery planning. This data can aid in understanding the spatial distribution and magnitude of the flood impact, assisting authorities in prioritizing relief efforts and allocating resources effectively for post-flood recovery and mitigation measures.

The flood has had a devastating impact on the cropland and urban/built-up areas in Larkana, Sukkur, Hyderabad, and their neighboring regions. The floodwaters have wreaked havoc, causing widespread destruction and disruption to these areas.

Needle leaf forests consist of coniferous trees with needle-like leaves, while broadleaf forests are dominated by trees with broad, flat leaves. Deciduous needleleaf forests combine both evergreen and deciduous tree species, while deciduous broadleaf forests shed their leaves seasonally. Mixed forests feature a combination of coniferous and broadleaf trees.

Closed shrublands are dense areas of woody shrubs, while open shrublands have a lower density and more open spaces. Woody savannas contain a mix of trees, shrubs, and grasses, whereas savannas are characterized by grasses and scattered trees. Grasslands are dominated by grasses without significant tree presence. Permanent wetlands are persistently saturated or covered by water, while croplands are used for agriculture. Urban and built-up lands represent

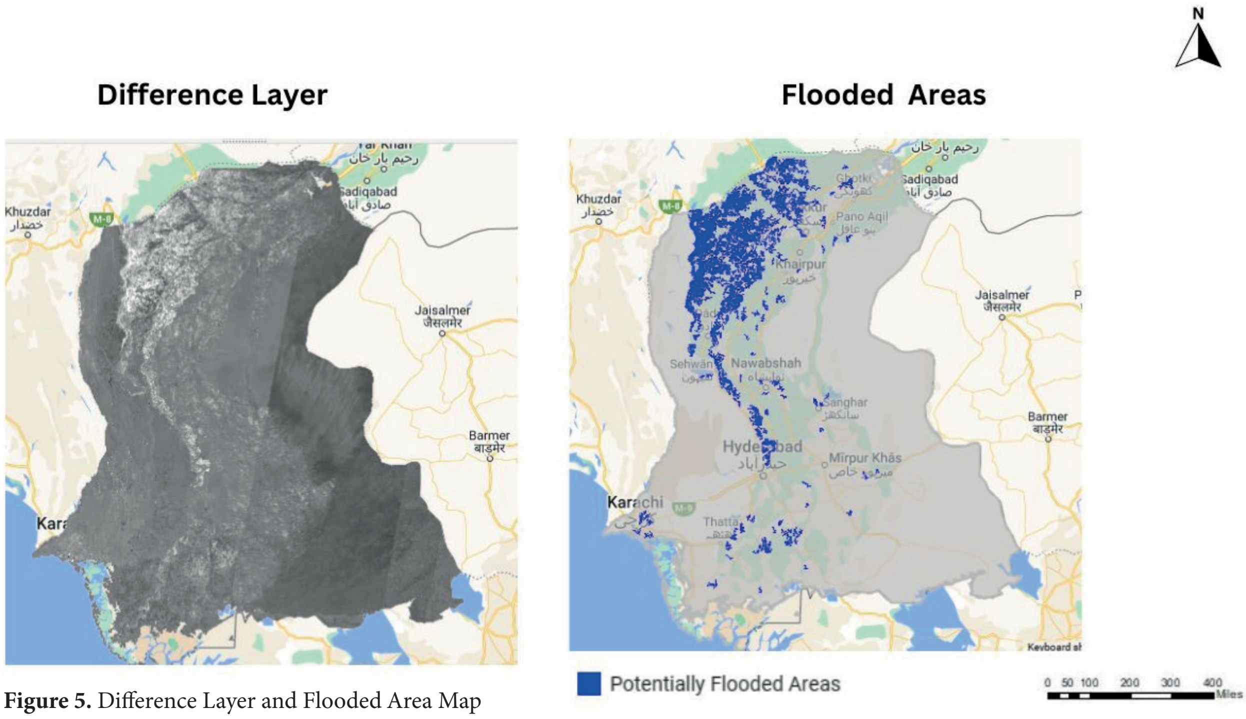

Figure 5. Difference Layer and Flooded Area Map

human settlements and infrastructure. Cropland/natural vegetation mosaics are landscapes with a mix of cultivated fields and natural vegetation (Fig. 6).

Approximately 687,962 hectares of cropland were affected by the 2022 flood in Sindh, Pakistan. This indicates a significant impact on agricultural areas in the region. Crop damage or inundation can have severe consequences for the local economy, food security, and livelihoods of farmers and communities dependent on agriculture (Fig. 7).

The Estimated Flood extent, Built-up/Urban Area, Affected Cropland and Number of Exposed Population by flood is about 759,642 ha, 8435 ha), 415,450 ha and 663,797 ha, respectively (Fig. 8).

Karachi, the largest city in Pakistan and the provincial capital of Sindh, stands out as a major urban center. It is a bustling metropolis and serves as the country's financial and economic hub, hosting various industries, corporate offices, educational institutions, and a vibrant cultural scene.

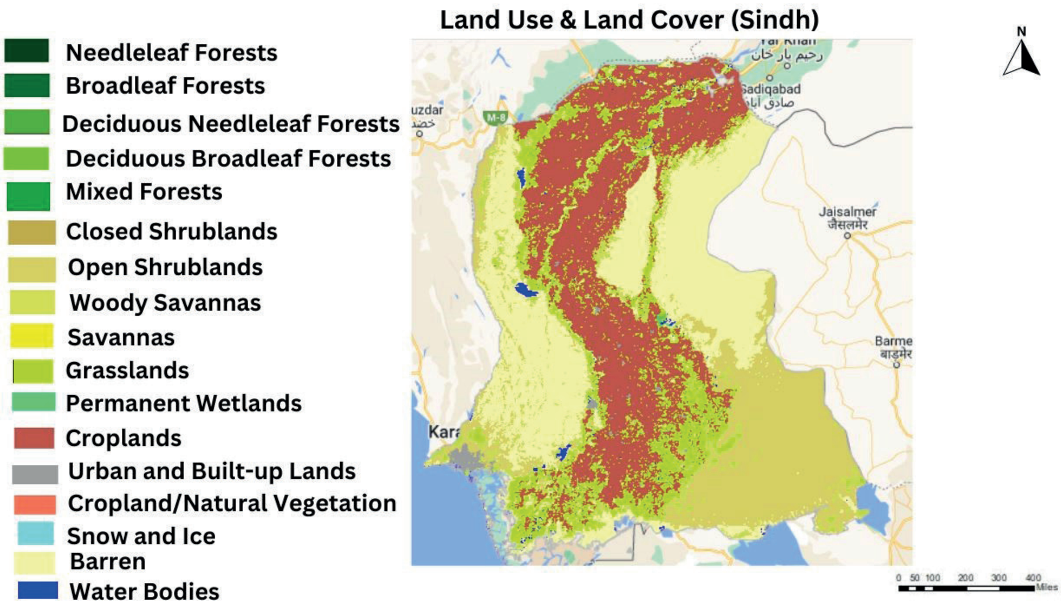

Figure 6. Land Use Land Cover Map

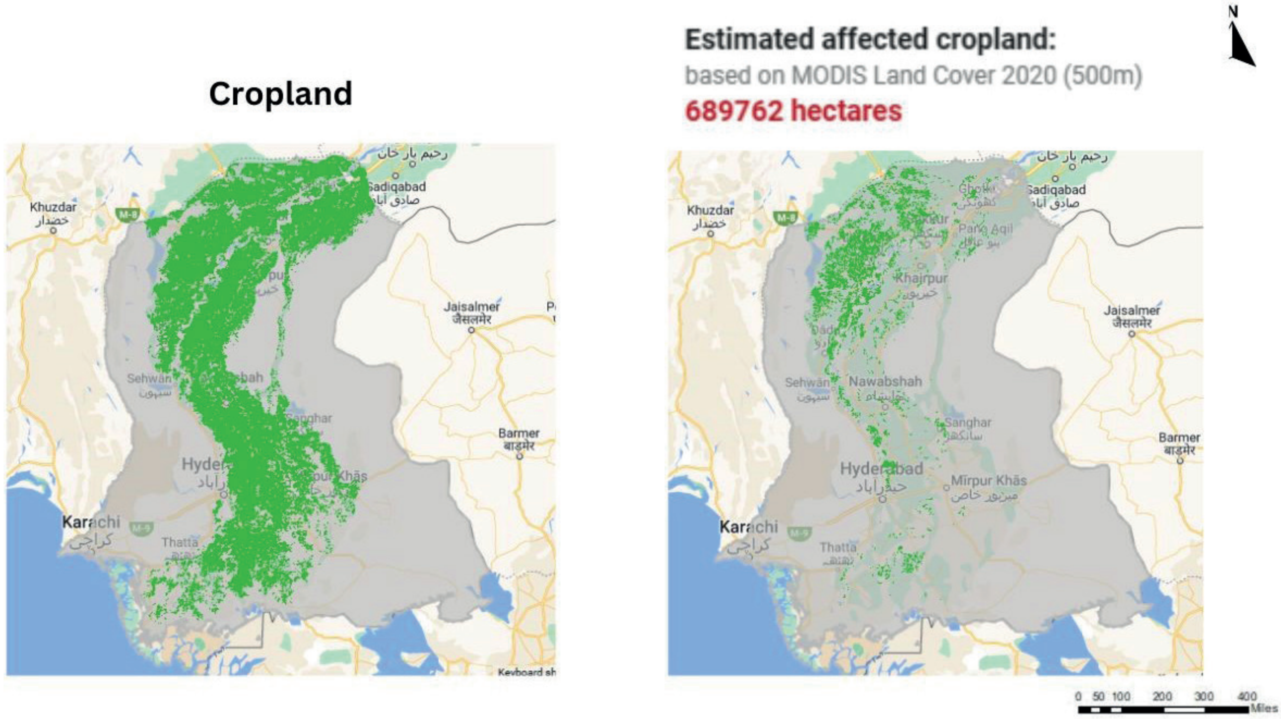

Figure 7. Normal Cropland and Estimated Affected Cropland

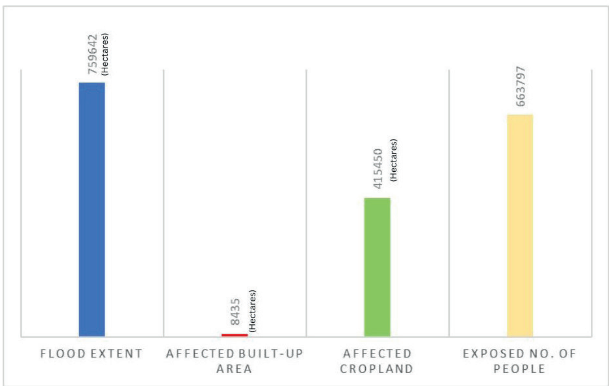

Figure 8. Statistics of Flood Extent, Affected Built-up and Cropland, and Exposed people

Karachi's urban landscape is characterized by high-rise buildings, shopping centers, markets, and a mix of residential neighborhoods (Fig. 9).

Approximately 156,001 hectares of land were affected by the flood in Sindh, Pakistan. This suggests a significant impact on the region's land cover, including croplands, urban areas, and natural vegetation. When floods occur, they can lead to the inundation of vast areas, causing damage to infrastructure, homes, agricultural fields, and disrupting livelihoods (Fig. 10).

5. Discussion

This study demonstrates the potential of utilizing Sentinel-1 SAR data and the Change Detection approach for flood mapping in Sindh, Pakistan. The results provide valuable information on the spatial extent of flooding, the number of affected people, and the impact on cropland and urban areas. These findings can guide flood management strategies, support decision-making processes, and contribute to building resilience in flood-prone regions. The results of this study have important implications for flood management and preparedness in Sindh, Pakistan. Accurate flood mapping enables authorities to develop effective mitigation and response strategies, such as early warning systems, evacuation plans, and infrastructure improvements. The information on affected cropland can guide agricultural policies and provide support to farmers affected by floods (Glavan et al., 2020). The availability of the Sentinel-1 full archive from the mission's initiation, coupled with its spatial and temporal resolution, makes it well-suited for timely flood mapping (Graw et al., 2022). The effectiveness of SAR images in flood inundation mapping is underscored by this research, contributing significantly to the calibration and validation of flood inundation models. Such mapping is of critical importance for authorities in making informed decisions during disaster situations (Ham & Kim, 2020). Future studies should consider employing classification methods such as

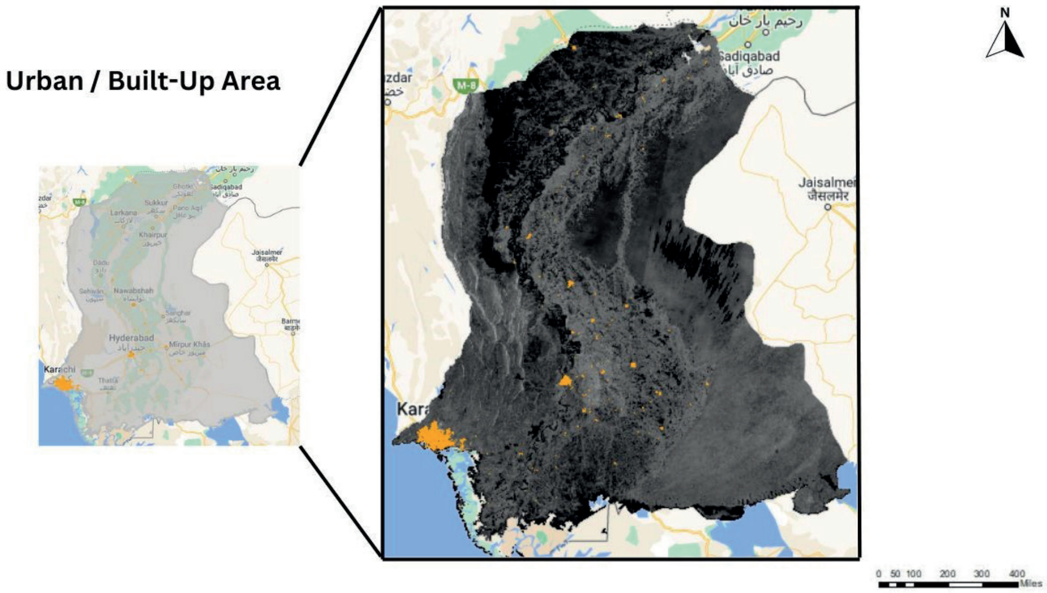

Figure 9. Urban / Built-Up Map

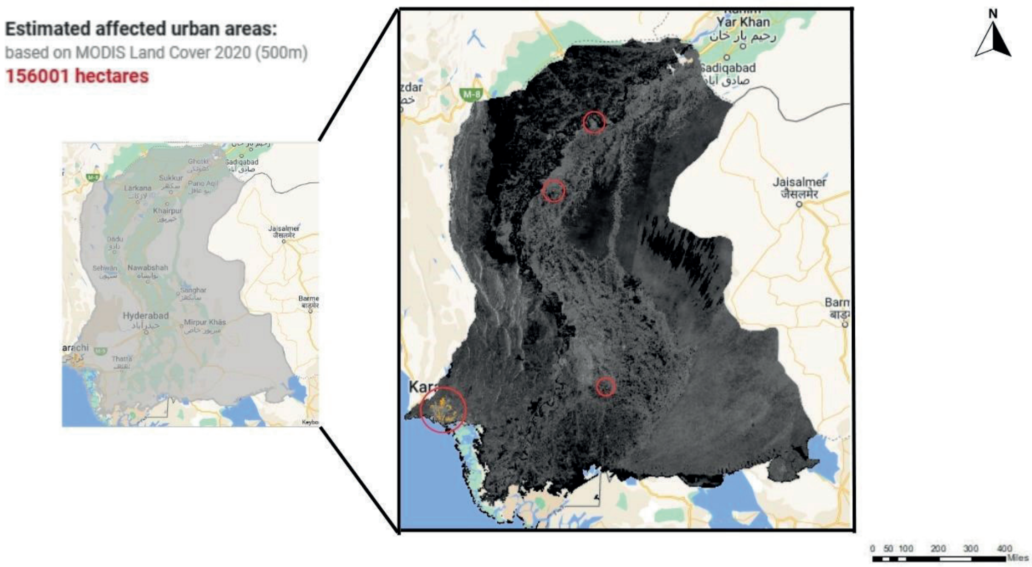

Figure 10. Estimated Affected Urban / Built-up Areas Map

machine learning and artificial intelligence techniques for flood mapping (Mastro et al., 2022). Flooding in Sindh, Pakistan, is a complex issue influenced by various factors, including climate change, deforestation, rapid urbanization, and inadequate infrastructure. The consequences of these floods are severe, affecting lives, livelihoods, and the overall socio-economic fabric of the province (Shahzad et al., 2021).

6. Conclusion

Floods are recognized as one of the most destructive natural disasters globally, resulting in significant economic and human losses. The purpose of this study was to estimate the Flood extent, Built-up/Urban Area, Affected Cropland & Number of Exposed Population by flood is about 759,642 hectares, 8435ha, 415,450 ha and 663,797 ha, respectively. The CDAT algorithm was utilized to segment the images into flooded and non-flooded areas by applying a specific threshold value. The high reported accuracies indicate the efficiency of this method. We use latest way to estimate the flood extant and its potential. Although the flood event studied encompassed pre-flood, during-flood, and post-flood imagery, a single threshold value was applied, simplifying the mapping of flooded areas. This study help to understand to total damage of cropland and estimate the effected population in Sindh, Pakistan during 2022 Flood.

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