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ML/AI Based Flood Mapping in Swat Watershed Using Sentinel-I and Sentinel-II Data

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This research uses Sentinel-1 and Sentinel-2 data for flood monitoring and mapping, with a focus on the accuracy and reliability of these remote sensing techniques in identifying flood inundation areas. The objectives of this study revolved around the accuracy and reliability of these techniques in detecting and mapping floodwaters. Water indices, namely NDWI and WRI, were utilized to extract floodwater areas and generate flood inundation maps. Additionally, flood extent maps were generated using Sentinel-1 data to complement the findings from Sentinel-2 data. The study implemented a multi-sensor and multi-index approach, considering both optical and radar data, to provide a comprehensive analysis of flood events. Image selection based on low cloud cover was employed to ensure high-quality and cloud-free imagery for accurate flood extent estimation. The selected images were processed using water indices, NDWI and WRI, which effectively captured the spatial distribution of floodwaters. The results revealed insights into the temporal variation and spatial distribution of flood extents, allowing for the identification of most affected areas. The analysis of Sentinel-2 imagery for July 2022 showcased a progressive intensification of the flood event, with the most affected regions being Charbagh, Mangora, Saidu Sharif, and Chakdara. The flood extents increased in August 2022, affecting areas such as Mangora, Saidu Sharif, Charbagh, Manglor, Barikot, and Chakdara. Furthermore, the flood extent in September 2022 indicated the persistence of floodwaters in areas with relatively fewer sloping surfaces. The integration of Sentinel-1 data provided enhanced comprehension into flood extents, particularly in challenging conditions such as high cloud cover or dense vegetation. The flood inundation maps generated from Sentinel-1 data complemented the findings from Sentinel-2 data, enhancing the accuracy and reliability of flood extent assessments. It is important to note that the high areas observed in the Sentinel-1 flood inundation maps are due to the mosaic of all the images acquired during the respective months. This approach includes all the water detected by Sentinel-1 from the 15 images, resulting in a larger affected area being shown. The flood inundation areas derived from Sentinel-1 data for July, August, and September were 129 km², 431 km², and 66 km², respectively. The analysis of Sentinel-1 data reveals that Kalam, Bahrain, and Madyan are highly vulnerable to intense flooding, as indicated by the high flood levels observed in these regions. The steep terrain, narrow valleys, and high rainfall intensity contribute to the heightened flood risk in these areas. The flood extents in Mangora, Saidu Sharif, and Barikot also reached significant levels, indicating widespread inundation in these regions. Overall, the study demonstrated the effectiveness of Sentinel-1 and Sentinel-2 data in flood monitoring and mapping. The multi-sensor and multi-index approach enhanced the reliability and robustness of the flood extent assessments, enabling better-informed decision-making processes for emergency response planning, resource allocation, and the implementation of effective flood mitigation strategies. The findings highlighted the importance of considering multiple indices and satellite data sources to obtain a comprehensive understanding of flood dynamics, while acknowledging the influence of cloud cover and other factors on the accuracy of the results.

NDWI (Normalized Difference Water Index), **WRI** (Water Ratio Index), **IW** (Interferometric Wide), **VH** (Vertical/Horizontal), (**NIR**) Near-Infrared, (**GEE**) Google Earth Engine

Keywords: Sentinel-1, Sentinel-2, Flood monitoring, Flood mapping, Water indices, NDWI, WRI, Flood extent, Remote sensing, Multi-sensor approach.

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Introduction:

Climate change, stemming from the rise in greenhouse gas emissions, is a pervasive global phenomenon that engenders extensive ramifications for the climate systems and ecosystems of our planet. The primary driver of climate change is global warming, a process characterized by the gradual rise in worldwide temperatures. With rising temperatures, the intricate equilibrium of the Earth's climate systems is disturbed, resulting in substantial repercussions for weather patterns and natural phenomena. [1]. The impacts of global warming are multifaceted and pose considerable challenges to societies worldwide. One of the most pronounced consequences is the alteration of precipitation patterns, leading to more frequent and intense extreme weather events. Floods, in particular, have emerged as a critical issue exacerbated by climate change. Floods are natural disasters characterized by the overflow of water onto normally dry land, causing widespread damage and disruption[2]. The rising global temperatures associated with climate change have led to an increased retention of moisture in the atmosphere. This enhanced moisture content results in intense and prolonged rainfall events, increasing the likelihood of flooding[3]. The consequences of floods are severe and multifaceted. They result in the loss of lives, destruction of infrastructure, displacement of communities, and negative economic impacts. Additionally, floods have a detrimental effect on water resources, altering the hydrological balance of river basins and exacerbating water scarcity issues.

Throughout its history, Pakistan has grappled with formidable riverine flooding challenges, frequently experiencing severe flood events. Over the years, Pakistan has been susceptible to major floods that have caused devastating impacts on human lives and the economy. Some of the notable flood events in Pakistan include the years 1973, 1976, 1988, 1992, 2010, 2011, 2014, 2015, and 2022. Global warming and climate change have led to significant alterations in precipitation patterns worldwide, resulting in an increased frequency and intensity of flood events. Pakistan, like many other regions, has witnessed the adverse impacts of these changes, particularly in terms of devastating floods. Within Pakistan, the River Swat Basin in Swat Districts has been significantly affected, experiencing severe flood events that have caused loss of lives, infrastructure damage, and disruption to communities [4].

The research problem tackled in this study pertains to the necessity for a thorough examination of flood dynamics and water-related metrics within the River Swat Basin, considering the influence of global warming and climate change. While various researchers in the past have explored flood events and water resources in other regions of Pakistan, there is a clear knowledge gap specific to the River Swat Basin. The challenges associated with floods in the region, coupled with changing climatic conditions, necessitate a focused investigation to understand flood dynamics, assess water-related indices, and develop effective flood management strategies [5].

This research is motivated by the imperative to address the ramifications of global warming and climate change, with a specific focus on the impact of floods in the River Swat Basin. The region has experienced severe flood events in recent years, leading to loss of life, displacement of communities, infrastructure damage, and economic losses. These events have emphasized the need for accurate and up-to-date information on flood dynamics, water-related indices, and effective flood management strategies.

The absence of an in-depth investigation dedicated to the River Swat Basin serves as an additional incentive for this research. Despite the significant impact of floods on the region and the challenges posed by climate change, there is a lack of in-depth analysis and understanding of flood dynamics and their implications for water resource management. By conducting this research, we aim to fill this knowledge gap and provide valuable insights for stakeholders, policymakers, and practitioners involved in flood management and water resource planning.

Furthermore, the floods in the River Swat Basin in 2022 were particularly devastating, causing immense suffering and highlighting the vulnerabilities of the region. These floods demonstrated the inadequacy of existing flood management strategies and emphasized the need for evidence-based approaches to mitigate and manage future flood risks effectively. Through an examination of the 2022 flood events, this research seeks to delve into the specific challenges encountered by the River Swat Basin and make valuable contributions to the development of precise flood mitigation strategies and measures for enhancing resilience. Remote sensing is a technique that involves the acquisition and interpretation of information about the Earth's surface using sensors mounted on satellites or aircraft. Utilizing remote sensing methods, especially those leveraging optical and radar data, offers valuable insights into the dynamics of floods and relevant water-related indicators.[6]. Optical sensors, as exemplified by those installed on the Sentinel-2 satellite, acquire imagery suitable for the computation of water-related metrics such as the Normalized Difference Water Index (NDWI). Meanwhile, Synthetic Aperture Radar (SAR) data from instruments like those aboard the Sentinel-1 satellite provide the capacity to identify and chart flood inundations, even in challenging weather conditions. The practical implications of this research extend to local communities, decision-makers, and relevant stakeholders in the River Swat Basin. The improved flood management strategies, water resource planning, and strengthened early warning systems resulting from this study can enhance the resilience of communities, reduce the socio-economic impact of floods, and promote sustainable development in the region.

Flood events have significant impacts on both river systems and human settlements. This subsection examines these impacts, considering ecological, geomorphological, and societal aspects. Ecologically, floods can influence river morphology, sediment transport, and habitat dynamics. They play a crucial role in shaping river channels, depositing sediments, and promoting ecological processes such as nutrient cycling and habitat creation. Floods also have implications for aquatic ecosystems, affecting fish populations, riparian vegetation, and overall biodiversity [7].

This comprehensive exploration of flood dynamics provides a solid foundation for understanding the complex nature of floods, their causes, and their impacts on both river systems and human settlements. It establishes the basis for the subsequent sections of the literature review, which will delve into remote sensing applications, water-related indices, flood management strategies, and studies in similar river basins. In summary, water-related indices are powerful tools in flood analysis, offering insights into water distribution, flood extent, and changes in water content. The introduction to water-related indices, the detailed exploration of the NDWI [8], and the discussion of other commonly used indices contribute to the understanding of their applications in flood assessment. Leveraging these indices provides valuable information for comprehensive flood analysis, supporting flood management strategies, and enhancing water resource planning in flood-prone areas.

Material and Method:

The Swat River is a major tributary of the Kabul River and plays a crucial role in the region's water resources and ecosystems. The geometry of Swat District is defined by its administrative boundaries, which are marked by political subdivisions such as tehsils, towns, and villages. These boundaries demarcate the extent of the district and its division into various administrative units. The district's shape and size influence its vulnerability to floods, as the topography and land use patterns within the district play a significant role in the hydrological processes and flood dynamics [9]. The study area and river basins were carefully chosen to focus on specific regions that are prone to flooding and encompass the areas of interest for the research. The following areas have been included in the study; Kalam, Bahrain, Madyan, Khwazakhela, Charbagh, Manglor, Mangora, Saidu Sharif, Barikot and Chakdara

These areas were selected based on their significance in terms of flood occurrence, vulnerability, and potential impact on local communities and infrastructure. They represent key locations within the larger study area that are prone to flooding events and can provide valuable insights into flood dynamics and patterns [10].

Data Collection:

For conducting this research, the data from Sentinel-1 and Sentinel-2 satellites was obtained through Google Earth Engine (GEE). GEE is a powerful cloud-based platform that provides access to a vast array of remote sensing and geospatial data. For the estimation of flood inundation maps, Sentinel-1 data was collected from the GEE platform. Specifically, three sets of images were obtained for the months of July, August, and September. Each set consisted of 15 Sentinel-1 images, capturing the area of interest in the River Swat Basin during those months.

Overall, the use of 15 Sentinel-1 images for each month, and calculating their mean using the GEE platform, enabled the researchers to generate reliable flood inundation maps for July, August, and September. This methodology ensured a comprehensive and accurate representation of the flood extents in the River Swat Basin during the specified months, contributing to a more in-depth understanding of flood dynamics in the study area. One of the key advantages of using Sentinel-2 data is its frequent revisits to the same area, typically every 2-3 days. This frequent revisit time enables capturing dynamic changes in water bodies, including floods, with a higher temporal resolution [11]. The ability to monitor water bodies at such short intervals is crucial for timely and accurate flood monitoring and analysis. Moreover, Sentinel-2 data provides high spatial resolution imagery, with certain bands having a resolution of 10 meters [12]. This fine spatial resolution allows for detailed mapping and analysis of water-related features, including flood extents, river channels, and water bodies within the study area.

By converting Band 11 to a 10-meter resolution, the study ensures the compatibility and consistency of the input data, enabling more reliable and meaningful analysis of water-related parameters. The resampled Band 11 contributes to more accurate and consistent water indices estimation, enhancing the overall performance and reliability of the study's flood mapping and analysis. The NDWI values range from -1 to 1, where higher positive values indicate the presence of water, while lower values or negative values indicate other land cover types such as vegetation or bare soil. By thresholding the NDWI values, floodwater areas can be extracted and differentiated from other land cover classes. The WRI (Water Ratio Index) index can be used to identify and monitor water bodies, including lakes, rivers, and reservoirs. It provides valuable information for water resource management, hydrological studies, and environmental monitoring [13]. The use of Sentinel-2 data, with its multispectral capabilities and high spatial resolution, allows for accurate and reliable calculation of the WRI index and facilitates the analysis of water dynamics over time.

Results and Discussion:

This section aims to present the results and discuss the findings of the study in relation to the research question and objectives. The primary objective of the research is to assess the effectiveness of using Sentinel-1 and Sentinel-2 data for flood monitoring and mapping. The research question focuses on the accuracy and reliability of these remote sensing techniques in identifying flood inundation areas. Through the application of water indices, namely NDWI and WRI, the study seeks to extract floodwater areas and generate flood inundation maps[14]. The NDWI index utilizes the spectral characteristics of water and vegetation in the Near-Infrared (NIR) and green bands, while the WRI index combines the green, red, and NIR bands to estimate the extent of floodwater. These indices provide valuable information for detecting and mapping flood events.

Indices Calculation:

Image Selection Based on Cloud Cover:

The selection of images with low cloud cover was driven by the need to obtain high-quality and cloud-free imagery for accurate flood extent estimation. Cloud cover can significantly hinder the visibility of the Earth's surface, particularly in optical satellite imagery such as Sentinel-2 data, which relies on visible and near-infrared bands for water detection. By choosing images with minimal cloud cover, the research aimed to minimize the potential for misclassification or ambiguity in identifying flooded areas.

This selection strategy was based on historical cloud cover patterns and climatic conditions specific to the study area. By selecting days with reduced cloud cover, the probability of obtaining clear, high-quality images that accurately depict the magnitude of the floodwater was heightened. The emphasis on obtaining images with minimal cloud cover aligns with the objective of achieving accurate and reliable flood extent mapping. Clear imagery allows for better discrimination between water and non-water areas, reducing uncertainties in the analysis. By minimizing the impact of cloud cover, the research aimed to enhance the precision and quality of the derived flood extent maps, thereby enabling more robust flood monitoring and management [15]. It is worth noting that while selecting images with low cloud cover increases the likelihood of capturing clear flood extent information, it is still important to consider the limitations and potential influence of residual clouds or cloud shadows in the imagery. These factors will be taken into account during the analysis and interpretation of the obtained flood inundation maps.

The Normalized Difference Water Index (NDWI):

NDWI for July-2022:

The flood inundation maps based on the NDWI for the images captured on 17th July and 27th July revealed important insights into the extent and intensity of the flooding in the study area. Here is a summary of the findings based on the two images:

Image of 17th July:

- The image shows a total flooded area of approximately 2,634 hectares.
- Among the selected areas, the most affected regions are Charbagh, Manglor, Mangora, Saidu Sharif, and Chakdara.
- These areas experienced significant flooding, indicating a substantial presence of water bodies and potential damage to infrastructure and communities.

Image of 27th July:

- The image indicates a higher intensity of floodwater compared to the image from 17th July.
- The total flooded area has increased to approximately 7565 hectares.
- With the exception of Kalam, all other nine areas experienced flooding.
- The areas most affected by the flood include Mangora and Saidu Sharif, followed by Charbagh and Khwazakhela.

These findings suggest a progressive intensification of the flood event between the two dates, with a larger area being affected by floodwaters on 27th July. The identified areas of Charbagh, Mangora, Saidu Sharif, and Chakdara consistently showed high vulnerability to flooding, indicating the need for focused flood management and mitigation measures in these regions. The analysis of these images provided valuable information on the spatial distribution of floodwaters, allowing for a better understanding of the extent and severity of the flooding in the study area. Figure 1 shows spatial temporal flood area for the month of July using NDWI. This knowledge can support decision-making processes related to emergency response, resource allocation, and long-term flood mitigation strategies [16].

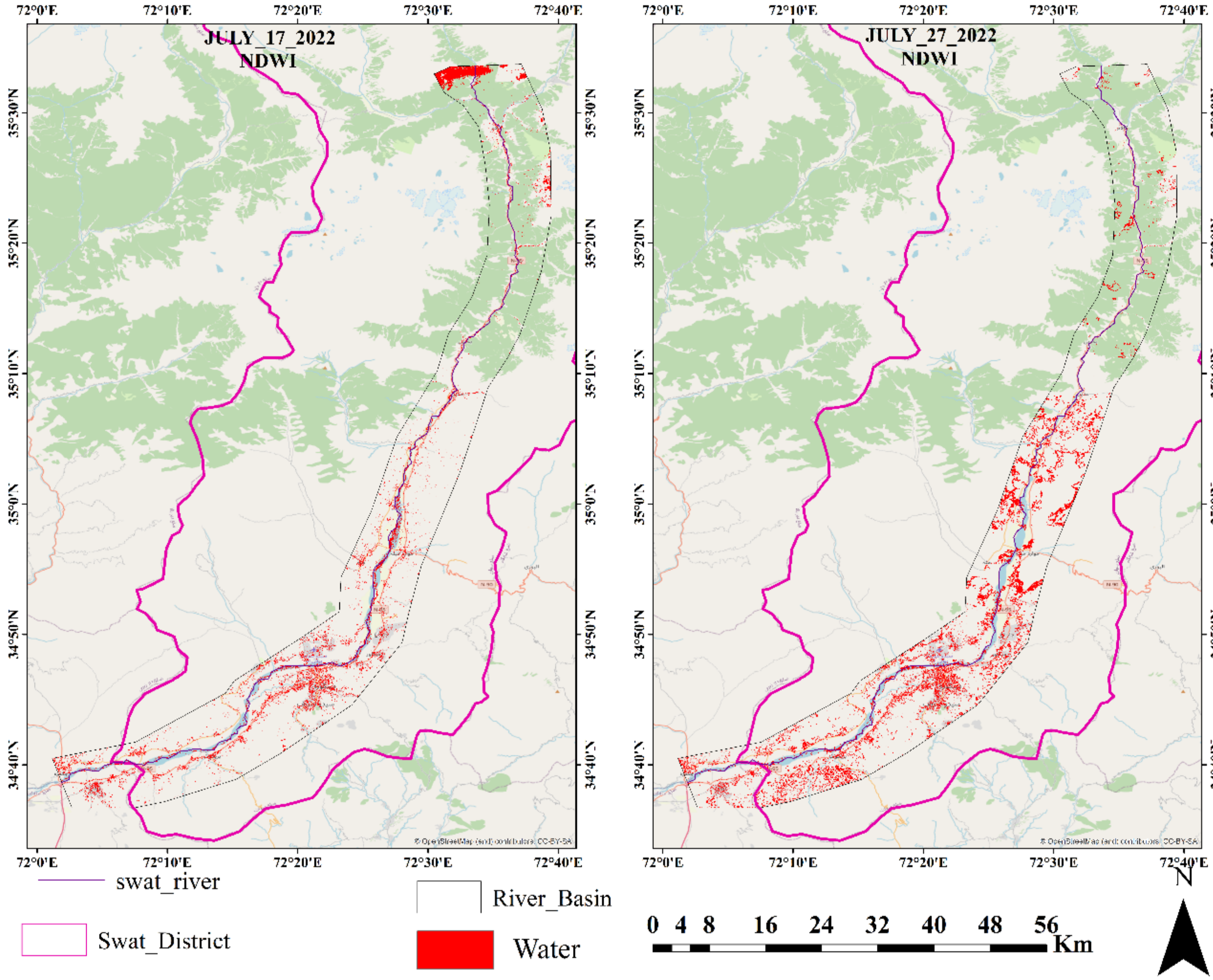

Figure 1: Spatial -temporal flood area extent for July month using the NDWI

NDWI for August-2022:

The analysis of Sentinel-2 satellite imagery for August 2022 provides valuable insights into the extent of floodwater in the study area. Three images were obtained on different days: 5th August, 13th August, and 28th August. These specific days were selected to ensure the acquisition of images with the lowest possible cloud cover, enhancing the quality and accuracy of the results. The selection of specific days for imagery acquisition was based on the aim of obtaining images with low cloud cover. Cloud cover can obstruct the visibility of floodwater and affect the accuracy of the results. By selecting days with minimal cloud cover, the study aimed to ensure clearer and more reliable floodwater mapping. This approach enhances the confidence in the obtained results and facilitates a more comprehensive understanding of the spatial distribution of flood extent in the study area [17]. On the 5th of August, the image revealed a water extent of approximately 8,629 hectares, which accounts for about 8% of the overall basin area. The most affected areas in this image were Mangora and Saidu Sharif, indicating localized flooding in these regions.

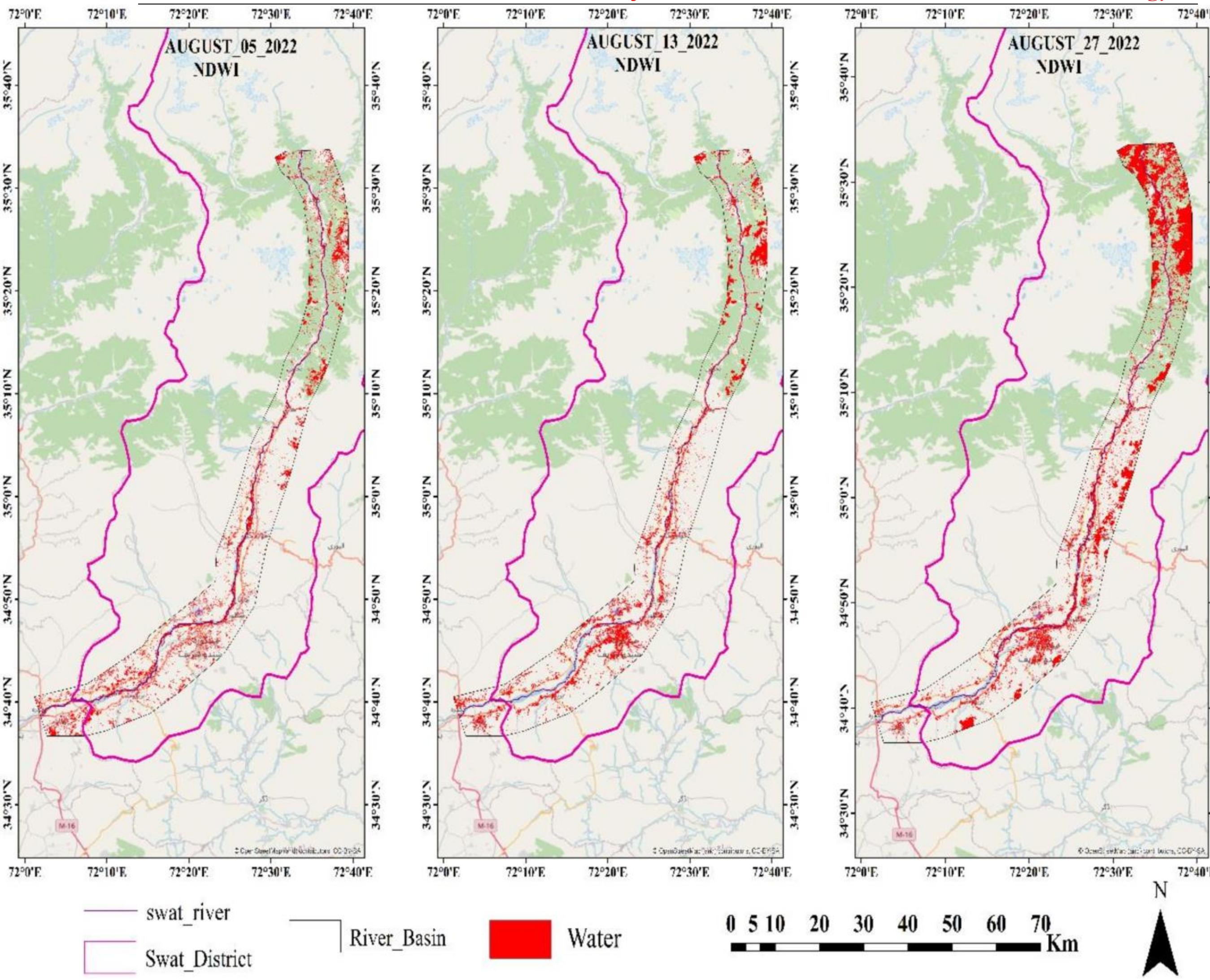

Figure 2: Spatial -temporal flood area extent for August month using the NDWI

Moving to the 13th of August, the floodwater extent increased significantly. The image showed an expanded water coverage of around 9,573 hectares, representing about 9% of the total basin area. Mangora and Saidu Sharif remained highly affected, and the flood extent expanded to other areas such as Charbagh, Manglor, Barikot, and Chakdara. The final image acquired on the 28th of August depicted the highest water content among the three images. The floodwater extent reached approximately 22,553 hectares, which accounts for about 21% of the total basin area. The most heavily affected areas shifted to Kalam and Bahrain, with substantial flooding observed in these regions. Additionally, all other districts in the study area exhibited a high vulnerability to flood extent, except for Chakdara. These findings underscore the progressive increase in the extent and intensity of the floodwater as the month of August advanced. Mangora, Saidu Sharif, and Chakdara consistently experienced significant floodwater presence, highlighting their high vulnerability to floods [18]. Moreover, the districts of Charbagh, Manglor, Barikot, Kalam, and Bahrain were also significantly affected in various images, indicating the need for targeted flood mitigation measures in these areas. Overall, the analysis of Sentinel-2 imagery for August 2022 provides critical insights into the temporal variation and spatial distribution of floodwater extent, enabling informed decision-making processes for emergency response planning, resource allocation, and the implementation of effective flood mitigation strategies in the study area.

NDWI for September-2022:

In the analysis of post-flood Sentinel-2 imagery for September, two images taken on the 6th and 16th of September were examined to assess the persistence of floodwater in the study area. The purpose was to determine whether the floodwaters had receded or if any residual water remained in the affected regions. The image acquired on the 6th of September indicated an overall water extent of approximately 6,514 hectares, which accounts for around 6% of the total basin area. The areas that were still affected by floodwaters were Mangora, Saidu Sharif, and some parts of Mangora. The presence of water in these areas could be attributed to their relatively fewer sloping surfaces, which may have caused water to accumulate and linger for a longer duration compared to other parts of the river basin. Moving to the image obtained on the 16th of September, it was observed that the affected areas still exhibited water presence. However, the extent of the floodwater had decreased to approximately 2,520 hectares, which accounts for about 2% of the total basin area. This reduction in the affected area suggests that the floodwaters were gradually receding [8].

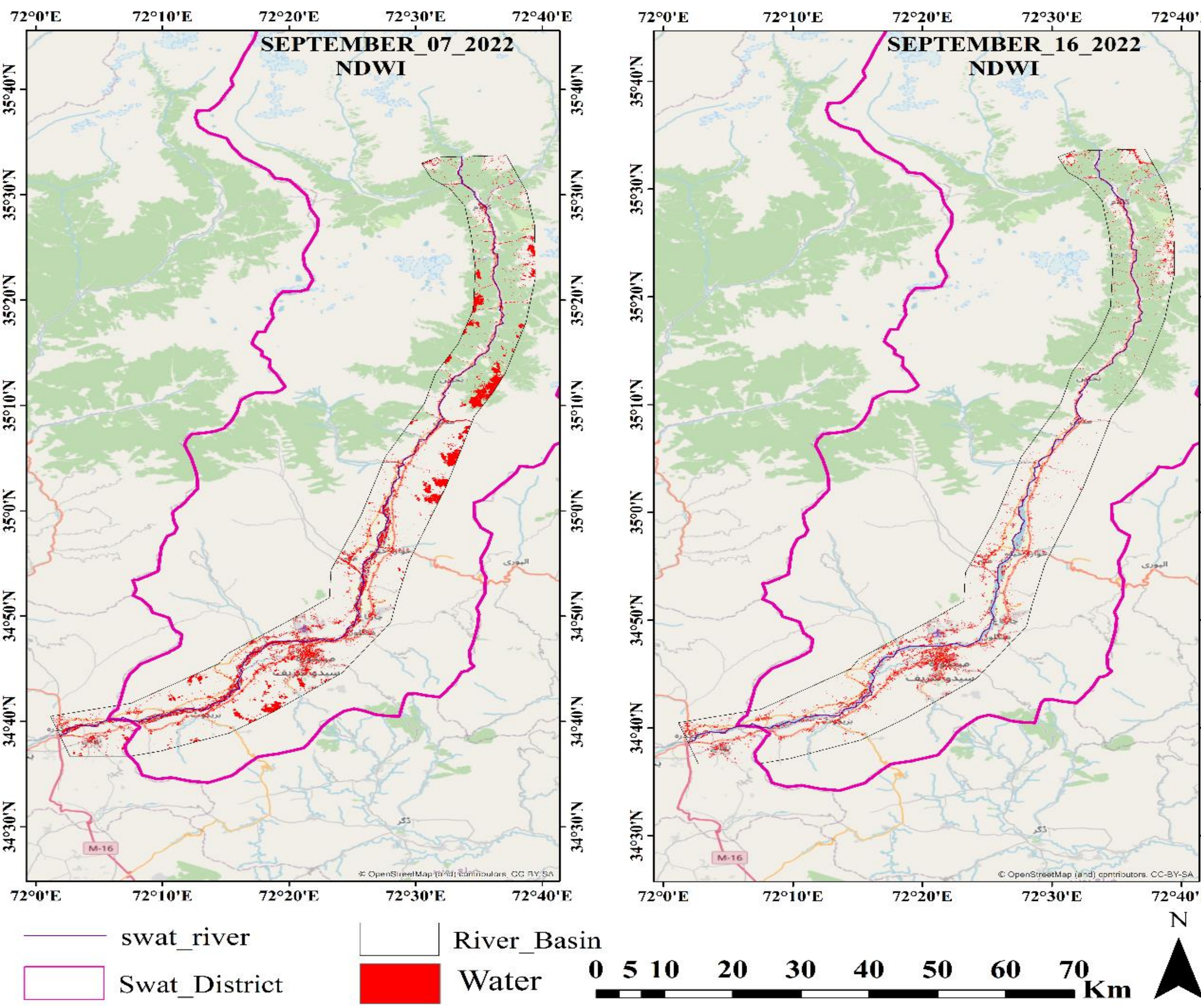

Figure 3: Spatial -temporal flood area extent for September month using the NDWI

These trends in the post-flood imagery demonstrate the effectiveness of using the NDWI for water detection in flooded areas. The index successfully identified the presence of water, even in the post-flood stage. However, it is important to note that the persistence of cloud cover and other factors can influence the accuracy and interpretation of the results. The persistent presence of water in the areas of Mangora, Saidu Sharif, and parts of Manglor in both images can be attributed to their topographical characteristics, such as flat or less sloping terrain. These areas are more prone to water accumulation and slower drainage, resulting in a longer duration of water presence. The analysis of September imagery highlights the importance of considering post-flood water extent to assess the duration and persistence of floodwaters [19]. The NDWI index proved effective in identifying water presence, and the observed trends provide valuable insights into the dynamics of the floodwaters in the study area. However, it is crucial to acknowledge the influence of cloud cover and other factors that may affect the accuracy and interpretation of the results. Figure 1, 2 and 3 illustrates the spatial temporal flood area extent for the months of July, August and September respectively using NDWI.

The Water Ratio Index (WRI):

In addition to the NDWI , the WRI (Water Ratio Index) was also calculated and analyzed to further assess the water extent and dynamics in the study area. The WRI index provides valuable insights into the water distribution and variability, allowing for a more comprehensive understanding of the flood event. The following sections present the results obtained from the analysis of the WRI index, including the interpretation of the images and the identification of water-affected areas [20].

WRI for July-2022:

In the analysis of the WRI images, it was observed that the water extent indicated by the WRI index was generally higher than that of the NDWI. For the image acquired on the 17th of July, the WRI index indicated a water extent of approximately 4,573 hectares, which is higher than the water extent observed using the NDWI index. The most affected regions by the floodwaters were Charbagh, Manglor, Mangora, Saidu Sharif, and Chakdara. Compared to the NDWI index, the WRI index showed a higher water extent of around 2% of the total basin area. Moving to the image obtained on the 27th of July, the water extent increased from 7,565 hectares (as indicated by the NDWI index) to 9,432 hectares (9% of the total basin area) when using the WRI index. The areas most affected by the floodwaters remained the same as observed in the NDWI analysis, including Mangora and Saidu Sharif, followed by Charbagh and Khwazakhela [21]. These findings suggested that the WRI index provides a more extensive representation of the water extent compared to the NDWI index. The higher water extent observed in the WRI analysis can be attributed to the inclusion of additional spectral bands (Green and Red) in the calculation of the index. These bands contribute to a more comprehensive assessment of water presence, especially in flood-affected regions.

The agreement between the affected areas identified by both the NDWI and WRI indices further supports the reliability of these indices for flood mapping and water extent analysis. The consistency in the most affected regions, such as Mangora, Saidu Sharif, Charbagh, and Khwazakhela, underscores the reliability of the indices in capturing the spatial distribution of floodwaters. The incorporation of the WRI index in the analysis enhances the assessment of water extent during flood events [22]. The index demonstrates its effectiveness in identifying and mapping flood-affected areas, with a larger water extent observed compared to the NDWI index. The findings highlighted the importance of utilizing multiple indices for a comprehensive understanding of flood dynamics and their impacts on the study area.

WRI for August-2022:

In the analysis of the WRI images for the month of August, which is known to be the most flooded month, the results showed similar trends to those observed in the NDWI analysis. For the image acquired on the 5th of August, both the WRI and NDWI indices indicated a water extent of approximately 9,519 hectares, accounting for around 9% of the total basin area. The most affected areas identified in this image were Mangora and Saidu Sharif, indicating localized flooding in these regions. The agreement between the WRI and NDWI results suggests the consistency in identifying flood-affected areas during this period [23].

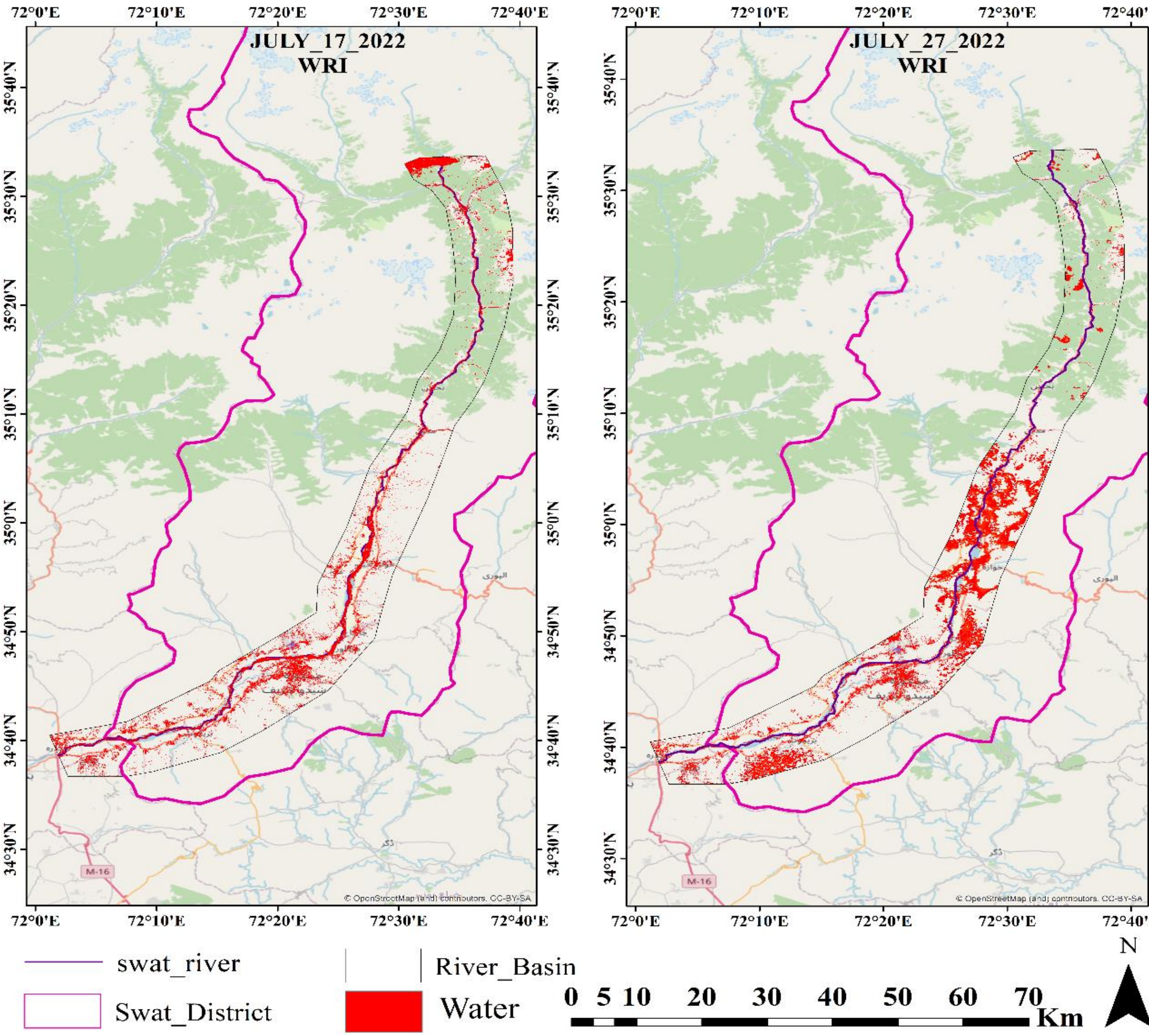

Figure 4: Spatial -temporal flood area extent for July month using the WRI.

Moving to the image acquired on the 13th of August, the water extent increased from 9,572 hectares (NDWI) to 12,962 hectares (3% increase) when using the WRI index. Mangora and Saidu Sharif remained highly affected, and the flood extent expanded to other areas, including Charbagh, Manglor, Barikot, and Chakdara. The WRI analysis captured the spatial dynamics of floodwaters, demonstrating its effectiveness in identifying the expansion of flood-affected regions compared to the NDWI analysis. For the final image acquired on the 28th of August, the water extent decreased from 22,602 hectares (21% of the total basin area) to 16,223 hectares (15% decrease) when using the WRI index. The most heavily affected areas shifted to Kalam and Bahrain, with substantial flooding observed in these regions. It is worth noting that, unlike the NDWI analysis, the WRI index also indicated the impact of flooding in Chakdara, highlighting the importance of incorporating additional spectral bands in the index calculation [24]. Figure 4 and 5 shows spatial-temporal flood are extent for the months of July and August respectively using WRI.

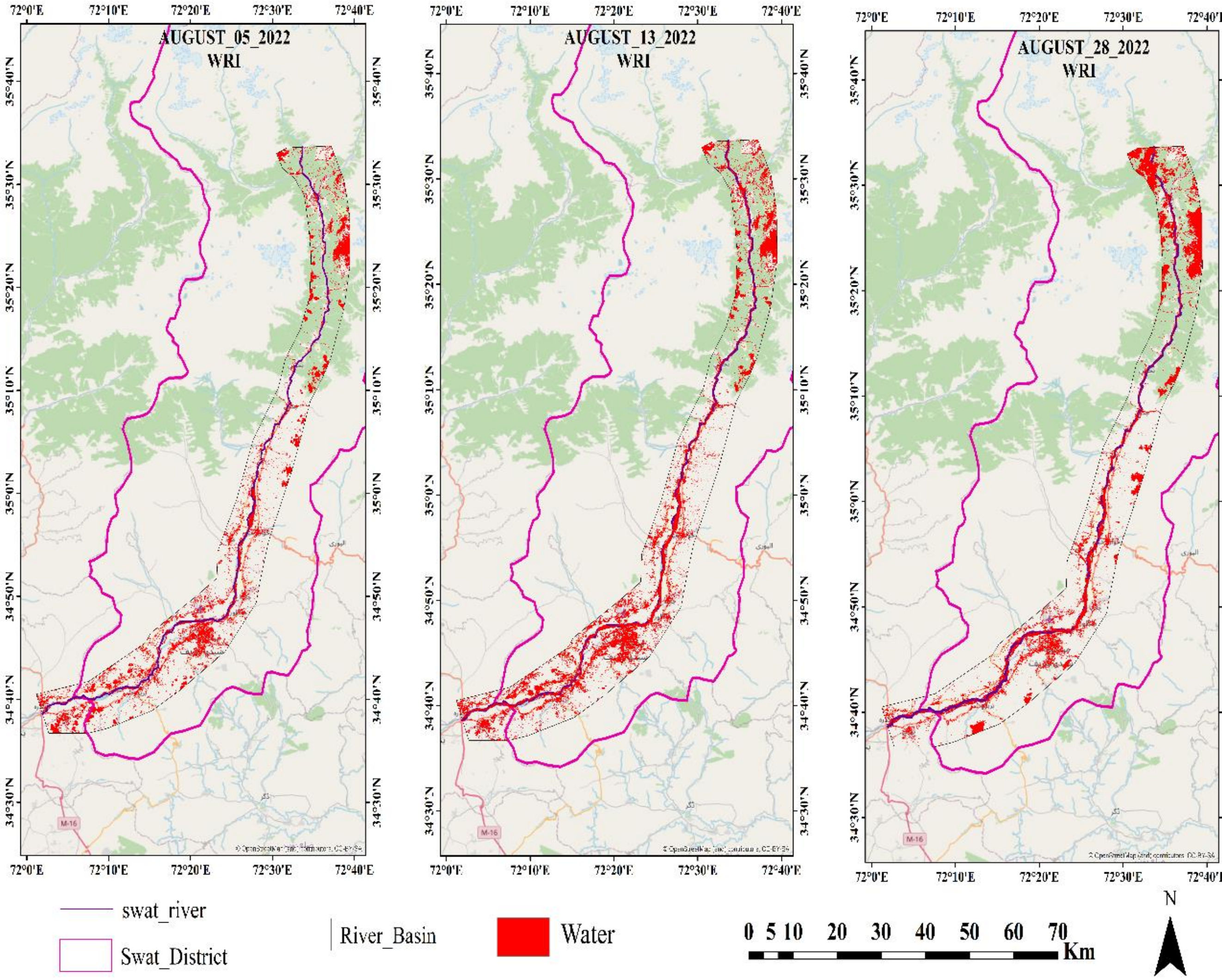

Figure 5: Spatial -temporal flood area extent for August month using the WRI

The results emphasized the capability of the WRI index in capturing the changes in flood extent and identifying the most affected areas. The agreement between the WRI and NDWI analyses confirms the reliability of both indices in mapping floodwaters. The observed differences in the affected areas between the two indices highlighted the complementary nature of the WRI index, which provides additional insights into the spatial distribution of floodwaters and enhances the overall understanding of flood dynamics in the study area. In summary, the WRI index proved valuable in assessing the water extent during the highly flooded month of August. It effectively identified and mapped flood-affected areas, showing consistency with the results obtained from the NDWI analysis. The inclusion of additional spectral bands in the WRI index calculation contributed to a comprehensive assessment of flood dynamics, capturing localized flooding and the expansion of flood extents in different regions [25].

WRI for post flood month (September-2022):

In September, the post-flood period, two images were obtained on the 6th and 16th of the month to assess the persistence of floodwaters. The results obtained from the WRI analysis revealed the presence of water in the study area, indicating the potential residual impacts of the floods.

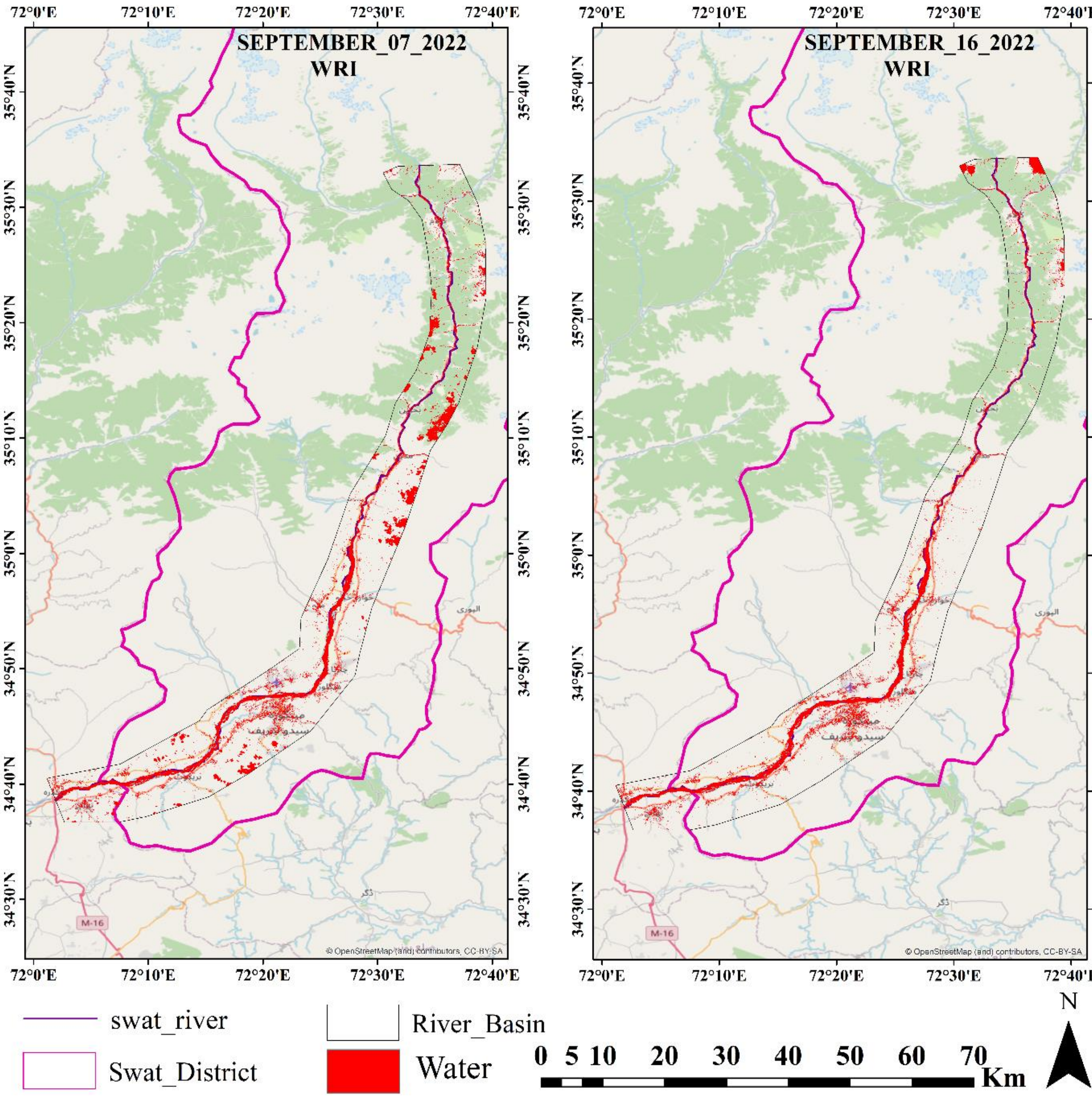

Figure 6: Spatial -temporal flood area extent for September month using the WRI

For the image acquired on the 6th of September, the WRI index identified an area of approximately 7,834 hectares (7% of the total basin area) still covered by water. This was slightly higher than the area identified using the NDWI, which was 6%. The areas that were still affected by floodwaters included Mangora, Saidu Sharif, and some parts of Manglor. The persistence of water in these areas could be attributed to their fewer sloping surfaces compared to other parts of the river basin, which hindered the rapid drainage of floodwaters. Moving to the image acquired on the 16th of September, it was observed that approximately 2,732 hectares (2.5%) of the area were still affected by floodwaters according to the WRI analysis. This was higher than the area identified using the NDWI analysis, which was 2,520 hectares. In above figure 6, it was notable that some areas of Kalam, which were missing in the NDWI analysis, were still affected by floodwaters. Additionally, Mangora and Barikot were identified as the most affected areas using this image.

The results of the WRI analysis in the post-flood period highlight the persistence of floodwaters in certain areas, indicating the slower drainage and accumulation of water in regions with less sloping terrain. The WRI index provided valuable information on the extent of water coverage, supplementing the findings from the NDWI analysis. The differences observed in the affected areas between the WRI and NDWI indices highlight the importance of considering multiple indices to gain a comprehensive understanding of post-flood conditions. Overall, the results demonstrated that the WRI index effectively captured the presence of water in the post-flood period, allowing for the identification of areas still affected by floodwaters. This information contributes to a better understanding of the long-lasting impacts of floods and helps in assessing the recovery and resilience of the study area in the aftermath of flooding events.

Flood Inundation Using Sentinel-1:

In addition to the flood extent maps derived from Sentinel-2 data using the NDWI and WRI indices, flood inundation maps were also generated using Sentinel-1 data. The Sentinel-1 data provides valuable information on flood conditions, especially in areas with high cloud cover or during nighttime when optical sensors are limited. For the flood inundation mapping using Sentinel-1 data, a total of 15 images were acquired for each month, including July, August, and September. These images were processed and filtered using speckle filtering techniques to reduce noise and enhance the visibility of flood signals. The filtered images were then combined using the mosaic function to create a single image representing the flood extent for each month. The mosaic function effectively merges multiple Sentinel-1 images to generate a composite image that reflects the cumulative flood extent over the respective month. This approach allows for a comprehensive representation of the flood conditions during the specific time periods.

The flood inundation maps generated from Sentinel-1 data provide additional insights into the spatial distribution of floodwaters, complementing the information derived from Sentinel-2 data. The inclusion of Sentinel-1 data enhances the accuracy and reliability of the flood extent assessment, especially in challenging conditions such as high cloud cover or in areas with dense vegetation. By integrating the flood inundation maps from both Sentinel-1 and Sentinel-2 data, a more comprehensive understanding of the flood dynamics and the extent of water coverage can be obtained. This multi-sensor approach improves the reliability and robustness of the flood mapping results, enabling better-informed decision-making and flood management strategies.

The flood inundation maps generated from Sentinel-1 data, in combination with the NDWI and WRI indices derived from Sentinel-2 data, provided a comprehensive assessment of the flood conditions in the study area. These maps contribute to the understanding of the spatial and temporal variations in flood extent, helping to identify the most affected areas and assess the overall impact of the floods on the region. It is worth noting that the utilization of both Sentinel-1 and Sentinel-2 data sets and the integration of various indices and flood mapping techniques contribute to a more accurate and comprehensive analysis of the flood events. This multi-sensor and multi-index approach enhances the reliability and effectiveness of flood monitoring and assessment, supporting decision-makers and stakeholders in implementing appropriate mitigation and adaptation measures.

Flood Inundation Extant for July-2022:

The flood inundation mapping using Sentinel-1 data for the month of July revealed a total flood area of approximately 12982 hectares, accounting for approximately 12% of the study area as indicated in figure 7. This information was obtained by creating a mosaic of all 15 available images from Sentinel-1 and utilizing the IW (Interferometric Wide) and VH (Vertical/Horizontal) polarization bands in Google Earth Engine. The analysis of the flood inundation map indicated that the areas most affected by the floods were Kalam, Bahrain, Mangora, Saidu Sharif, Barikot and Madyan. These regions are characterized by high altitudes, which can contribute to increased susceptibility to flooding due to steep terrain and higher water runoff. Conversely, the lower altitude areas within the study area were relatively less affected by the floods. By incorporating the Sentinel-1 data, which is based on radar technology, the flood extent mapping provides additional insights into the areas affected by the floods. Radar data is less influenced by atmospheric conditions, such as cloud cover, and can penetrate through vegetation, allowing for a more accurate assessment of flood extent.

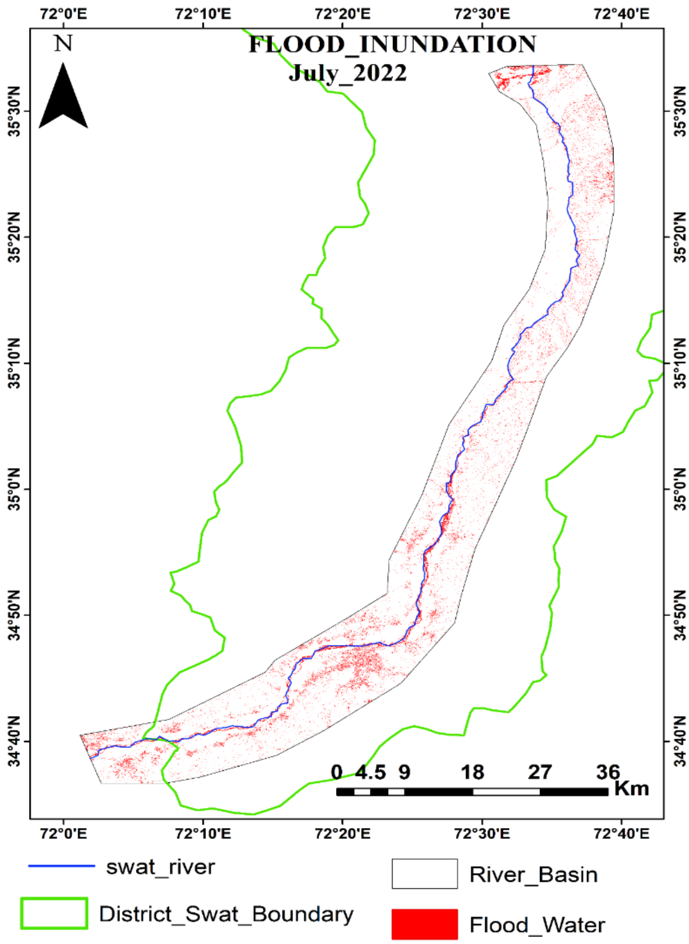

Figure 7: Sentinel-1 flood inundation map for July-200

The inclusion of high-altitude areas, such as Kalam, Bahrain, and Madyan, among the most affected regions highlights the role of topography in influencing flood dynamics. The steep slopes and narrow valleys in these areas can exacerbate the flow of water, leading to increased flood inundation. Overall, the integration of Sentinel-1 data in the flood inundation mapping enhances the understanding of the spatial distribution of floodwaters and helps identify the areas that are most susceptible to flooding. This information can be valuable for disaster management and planning authorities to implement appropriate measures for flood mitigation and preparedness in the affected regions.

Flood Inundation Extant for August-2022:

In the case of flood inundation mapping for the month of August, the mosaic of all the available images from Sentinel-1 revealed a significant extent of flooding. The analysis of this map indicates that approximately 40% of the study area, accounting for about 43,126 hectares, was experiencing floods during this period. The flood extent map clearly depicts the severity of the floods, with many locations experiencing severe to extreme flood conditions. Among the most affected areas, Kalam stands out as the region experiencing the highest flood extent. Following Kalam, areas such as Bahrain, Madyan, Mangora, Saidu Sharif, and Barikot also experienced high flood events.

The high flood levels in Kalam, Bahrain, and Madyan highlight the vulnerability of these regions to intense flooding. Factors such as steep terrain, narrow valleys, and high rainfall intensity contribute to the heightened flood risk in these areas. The presence of such severe flood conditions indicates the potential for significant damage to infrastructure, agriculture, and livelihoods in these regions. The flood extent in Mangora, Saidu Sharif, and Barikot also reached significant levels, indicating widespread inundation in these areas. The severity of the floods underscores the importance of comprehensive flood management strategies and early warning systems to mitigate the potential impacts on communities and infrastructure. Figure 8 shows Sentinel 1 flood induction map for August 2002.

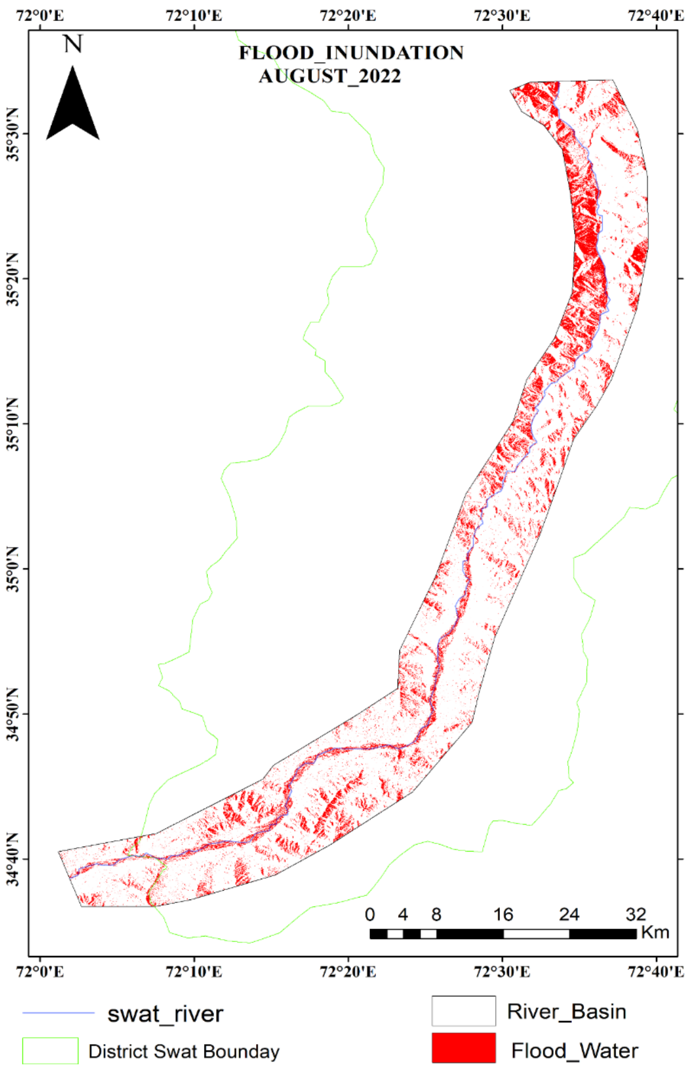

Figure 8: Sentinel-1 flood inundation map for August-2002

By utilizing the Sentinel-1 data and generating the flood inundation map for August, a detailed understanding of the spatial distribution and severity of the floods can be obtained. This information is crucial for disaster response and recovery efforts, as it enables targeted interventions and resource allocation to the most affected areas. Overall, the flood inundation mapping for August highlights the widespread nature of the floods, with a significant portion of the study area experiencing severe inundation. This information can support decision-makers and disaster management authorities in developing effective strategies for flood mitigation, preparedness, and response in the affected regions.

Flood Inundation Extant for September-2022:

In the month of September, which is the post-flood period, the flood inundation mapping using Sentinel-1 data indicated that an area of approximately 6,624 hectares, accounting for approximately 6% of the total study area, remained under flood extent as indicated in figure 9. This information was obtained by analyzing a mosaic image generated from the 15 available Sentinel-1 images for the month of September. The analysis of the flood extent in the post-flood month provides insights into the persistence of floodwaters and the areas that are still affected. High-altitude regions such as Kalam, Bahrain, and Madyan were observed to still have floodwaters, indicating the slow receding process in these areas. On the other hand, low-lying areas experienced a relatively lower impact and were less affected by the floodwaters during this period.

The inclusion of Sentinel-1 data in the flood inundation mapping allows for the identification and monitoring of post-flood water bodies, aiding in the assessment of the flood recovery process. This information is valuable for understanding the long-term impacts of flooding and facilitating appropriate measures for rehabilitation and mitigation efforts in the affected areas. By combining the flood inundation maps from different months and sources, a comprehensive understanding of the flood dynamics and their impacts on different regions can be obtained. This integrated approach facilitates a better assessment of the flood situation and aids in decision-making processes for effective flood management and mitigation strategies.

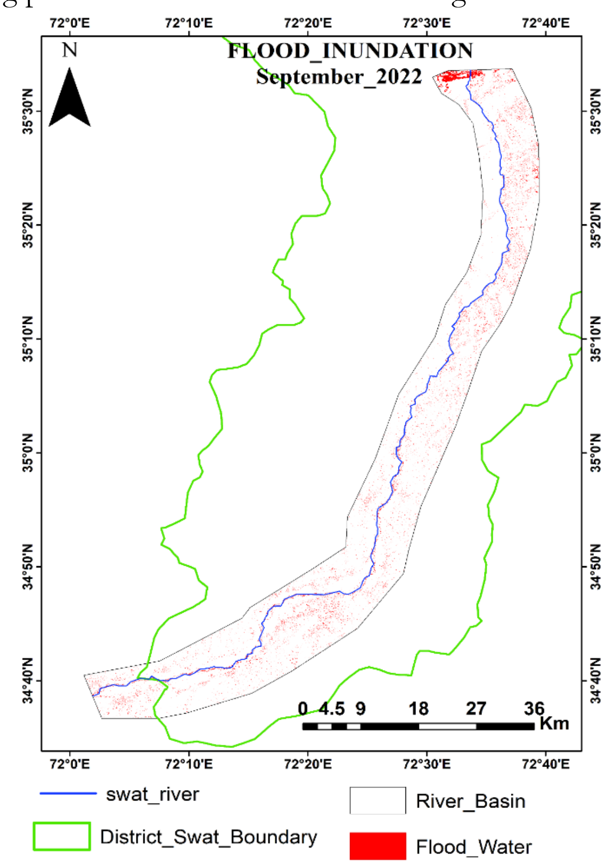

Figure 9: Sentinel-1 flood inundation map for September-2002

The discussion section aims to interpret and analyze the obtained results in relation to the research question and objectives. The primary objective of the study was to assess the effectiveness of using Sentinel-1 and Sentinel-2 data for flood monitoring and mapping, specifically focusing on the accuracy and reliability of these remote sensing techniques in identifying flood inundation areas. The analysis was conducted using water indices, including NDWI and WRI, to extract floodwater areas and generate flood inundation maps. The selection of images with low cloud cover was crucial to ensure high-quality and cloud-free imagery for accurate flood extent estimation. The strategy of selecting days with minimal cloud cover based on historical patterns and climatic conditions specific to the study area aimed to minimize misclassification and ambiguity in identifying flooded areas. By minimizing the impact of cloud cover, the research aimed to enhance the precision and quality of the derived flood extent maps, enabling more robust flood monitoring and management. The results obtained from the NDWI analysis for July 2022 revealed important insights into the extent and intensity of flooding in the study area. The images captured on 17th July and 27th July showed a progressive intensification of the flood event, with a larger area being affected by floodwaters on 27th July. The identified areas of Charbagh, Mangora, Saidu Sharif, and Chakdara consistently showed high vulnerability to flooding, indicating the need for focused flood management and mitigation measures in these regions.

Moving to the analysis of the NDWI images for August 2022, the results demonstrated the temporal variation and spatial distribution of floodwater extent. The images captured on 5th August, 13th August, and 28th August provided valuable insights into the increasing water extent and the most affected areas. The analysis showed that Mangora and Saidu Sharif remained highly affected throughout the month, while the flood extent expanded to other areas such as Charbagh, Manglor, Barikot, and Chakdara. The progressive increase in the extent and intensity of the floodwaters emphasized the need for targeted flood mitigation measures in these areas. In September 2022, the post-flood period, the analysis of NDWI images on 6th September and 16th September indicated the persistence of floodwaters in certain areas. Mangora, Saidu Sharif, and some parts of Manglor were still affected, suggesting the slower drainage and accumulation of water in regions with less sloping terrain. The findings highlighted the effectiveness of the NDWI index in identifying water presence, even in the post-flood stage, but acknowledged the influence of cloud cover and other factors on the accuracy and interpretation of the results. The results obtained from the WRI analysis complemented the findings from the NDWI analysis, providing additional insights into the water distribution and variability. The WRI index showed a higher water extent compared to the NDWI index, indicating its effectiveness in capturing the spatial dynamics of floodwaters. The agreement between the affected areas identified by both indices further supported their reliability for flood mapping and water extent analysis.

The flood inundation maps generated from Sentinel-1 data using IW and VH polarization bands provided additional insights into the spatial distribution of floodwaters. The analysis revealed significant flood extents in July, August, and September 2022, with high-altitude areas such as Kalam, Bahrain, and Madyan experiencing the highest flood levels. The integration of Sentinel-1 data enhanced the accuracy and reliability of the flood extent assessment, particularly in challenging conditions such as high cloud cover or dense vegetation. In conclusion, the results obtained from the analysis of Sentinel-2 and Sentinel-1 data using NDWI, WRI, and flood inundation mapping techniques provided valuable information on the extent, intensity, and spatial distribution of floodwaters in the study area. The findings demonstrated the effectiveness of remote sensing techniques in flood monitoring and mapping, allowing for better-informed decision-making processes related to emergency response, resource allocation, and long-term flood mitigation strategies. The study highlighted the importance of considering multiple indices and satellite data sources for a comprehensive understanding of flood dynamics, while acknowledging the influence of cloud cover and other factors on the accuracy of the results.

Conclusion:

This research aimed to assess the effectiveness ofSentinel-1 and Sentinel-2 data for flood monitoring and mapping. Through the application of water indices such as NDWI and WRI, combined with the analysis of flood inundation maps, generated from Sentinel-1 data, valuable insights into the spatial distribution and extent of floodwaters were obtained. The results of the study indicated that both Sentinel-1 and Sentinel-2 data are reliable and effective sources for flood monitoring and mapping. The NDWI and WRI indices derived from Sentinel-2 data successfully identified and mapped flood-affected areas, providing valuable information on the extent and intensity of flooding events. The inclusion of Sentinel-1 data enhanced the accuracy and reliability of the flood extent assessments, particularly in challenging conditions such as high cloud cover or dense vegetation.

The analysis of the flood extent maps revealed specific areas that are highly vulnerable to intense flooding. Regions such as Kalam, Bahrain, Madyan, Mangora, Saidu Sharif, and Barikot consistently experienced significant flood extents, indicating the need for focused flood management and mitigation measures in these areas. The topographical characteristics of steep terrain, narrow valleys, and high rainfall intensity contribute to the heightened flood risk in these regions. The findings from this research contribute to a better understanding of flood dynamics and their impacts on the study area. The integration of multiple indices and satellite data sets allows for a comprehensive assessment of flood events, enabling informed decision-making processes for emergency response planning, resource allocation, and the implementation of effective flood mitigation strategies.

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