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Application of SAR-Driven Flood Detection Systems in Wetland Ecosystems and its Implications for Migratory Bird Habitat Management

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Abstract: Wetland ecosystems play a vital role in maintaining global biodiversity, hydrological stability, and carbon sequestration. However, these ecologically sensitive areas are increasingly threatened by climate-induced flooding, anthropogenic disturbances, and habitat degradation. Synthetic Aperture Radar (SAR) technology has emerged as a powerful remote sensing tool for real-time, all-weather flood detection, offering high-resolution imagery critical for wetland monitoring and adaptive ecosystem management. This review explores the application of SAR-driven flood detection systems in tracking water level fluctuations and inundation patterns within wetlands and evaluates their implications for migratory bird habitat conservation. Emphasis is placed on SAR's capability to penetrate cloud cover and detect changes in surface moisture, which enhances early flood warning systems and informs decision-making for habitat protection. The paper also investigates case studies where SAR data have been integrated into conservation planning, emphasizing spatiotemporal analysis for managing seasonal wetlands that serve as critical stopover or breeding sites for migratory birds. By highlighting technological advancements, methodological approaches, and interdisciplinary frameworks, the review highlights the potential of SAR to support resilient wetland management strategies that align with global conservation goals.

Keywords: *Synthetic Aperture Radar (SAR), Flood Detection, Wetland Ecosystems, Migratory Birds, Habitat Management.*

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I. INTRODUCTION

- *Background on Wetland Ecosystems and their Ecological Significance*

Wetland ecosystems represent some of the most productive and ecologically valuable landscapes on Earth. They provide critical services including flood regulation, water purification, carbon sequestration, and biodiversity support. Wetlands act as ecological buffers by absorbing excess rainfall, filtering pollutants from runoff, and maintaining hydrological balance, especially in low-lying regions prone to inundation. According to Mitsch and Gosselink (2015), wetland restoration contributes significantly to mitigating climate change impacts by enhancing carbon storage and stabilizing local climates. These ecosystems also support complex food webs, offering essential breeding, nesting, and foraging grounds for aquatic and terrestrial species, including migratory birds that depend on seasonal wetland cycles for survival.

The loss and degradation of wetlands have accelerated over the past century due to urbanization, agricultural expansion, and infrastructure development. Davidson (2014) emphasized that the world has already lost approximately 64–71% of its natural wetland area since 1900, leading to alarming declines in ecosystem functions and services. This rapid transformation disrupts not only biogeochemical cycles but also the migration pathways of avian species that rely on intact wetland networks. The ecological fragility and strategic location of wetlands highlight the urgency of integrating real-time monitoring technologies, such as SAR systems, to

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ensure their sustainable management amid environmental and anthropogenic stressors.

➢ *Threats from Climate-Induced Flooding and Human Activities*

Wetland ecosystems are increasingly imperiled by the synergistic effects of climate-induced flooding and anthropogenic activities. In the Liaohe River Delta, human interventions such as agricultural expansion, aquaculture, and urban development have led to significant alterations in wetland landscapes. These activities have transformed natural wetlands into fragmented patches, disrupting hydrological regimes and diminishing biodiversity. Deng et al. (2024) utilized remote sensing data to analyze land use changes from 1995 to 2020, revealing a consistent decline in natural wetland areas, primarily due to intensified human activities. The study highlights that the conversion of wetlands into paddy fields and construction sites has exacerbated habitat fragmentation, leading to a loss of ecological integrity.

Climate change further compounds these challenges by altering precipitation patterns and increasing the frequency of extreme weather events. In the Pantanal region, one of the world's largest tropical wetlands, proposed infrastructural projects like the Paraguay-Paraná waterway threaten to disrupt natural flooding cycles. Junk, & de Cunha (2005) argue that such developments could reduce the floodplain's extent, making the ecosystem more susceptible to droughts and wildfires. The study emphasizes that the combination of reduced inundation and rising temperatures has already led to unprecedented wildfire events, endangering the region's rich biodiversity and carbon storage capacity. These findings highlight the critical need for integrated management approaches that consider both climatic and anthropogenic pressures to safeguard wetland ecosystems.

➢ *Importance of Monitoring Tools for Habitat Conservation*

Effective habitat conservation hinges on the deployment of precise and reliable monitoring tools that can detect ecological changes and inform management strategies. Environmental DNA (eDNA) metabarcoding has emerged as a transformative method, enabling the detection of species presence through genetic material collected from environmental samples such as soil or water. This technique allows for non-invasive monitoring of biodiversity, particularly in aquatic ecosystems where traditional survey methods may be challenging. However, the accuracy of eDNA analyses can be compromised by false positives, often resulting from contamination or sequencing errors. Ficetola et al. (2016) emphasize the necessity of stringent laboratory protocols and the inclusion of negative controls to mitigate these risks, thereby enhancing the reliability of eDNA as a monitoring tool.

In parallel, advancements in animal tracking technologies have significantly contributed to our understanding of species movements and habitat utilization. The integration of GPS telemetry and biologging devices facilitates the collection of high-resolution data on animal locations, behaviors, and interactions with their environment (Ijiga et al., 2024). Kays et al. (2015) discuss how these tools have revolutionized ecological research by providing insights into migration patterns, habitat preferences, and responses to environmental changes. Such information is critical for identifying essential habitats, assessing the impacts of anthropogenic pressures, and implementing targeted conservation measures. The synergy between molecular techniques like eDNA metabarcoding and spatial tracking technologies offers a comprehensive framework for monitoring biodiversity and guiding effective habitat conservation efforts.

➢ *Objectives and Scope of the Review*

The primary objective of this review is to critically examine the application of Synthetic Aperture Radar (SAR)-based flood detection systems in monitoring wetland ecosystems and to assess their implications for migratory bird habitat management. With increasing pressures from climate variability and anthropogenic modifications, the need for advanced, real-time ecological monitoring tools has become urgent. SAR technology, owing to its ability to penetrate cloud cover and operate under all weather conditions, is uniquely suited to flood-prone wetland environments. Xu et al. (2023) highlight that while SAR applications have advanced significantly in hydrological modeling and wetland delineation, gaps remain in ecosystem-specific interpretations and policy translation, particularly for biodiversity conservation.

This review also aims to contextualize the utility of SAR within the broader conservation framework for migratory birds. Migratory avian species are highly dependent on the dynamic hydrology of wetlands for breeding, roosting, and stopover functions. Martínez et al. (2022) demonstrate that integrating SAR data with species distribution models enhances the predictive capacity of habitat shifts under climate stressors. The scope of the paper thus encompasses SAR imaging principles, flood detection methodologies, case studies in wetland regions, and applications in avian conservation planning. Ultimately, this review provides a comprehensive foundation for interdisciplinary strategies that bridge technological innovation and ecological stewardship.

➢ *Structure of the Paper*

This review paper is structured into seven main sections, beginning with an introduction that outlines the ecological importance of wetlands, the growing threats from climate-induced flooding and human interference, and the critical need for advanced monitoring tools such as Synthetic Aperture Radar (SAR). Section examines the technical foundations and operational capabilities of SAR technology, highlighting its advantages over traditional optical systems. Section 3 explores specific methodologies and case studies involving SAR-driven flood detection in wetland ecosystems. Section 4 focuses on the ecological consequences of flooding on migratory bird habitats, examining the spatial and temporal dynamics critical to avian conservation. Section 5 discusses how SAR data can be integrated into real-time habitat management and policy-making frameworks. Section 6 provides insights into recent technological advancements, such as AI integration and multi-sensor fusion, that enhance

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SAR's ecological utility. Finally, Section 7 concludes the paper by summarizing key findings and offering strategic recommendations for future research, interdisciplinary collaboration, and policy interventions aimed at protecting wetland biodiversity through remote sensing innovation.

II. SYNTHETIC APERTURE RADAR (SAR) TECHNOLOGY OVERVIEW

➢ *Principles and Working Mechanism of Synthetic Aperture Radar (SAR)*

Synthetic Aperture Radar (SAR) is an advanced remote sensing technology that utilizes the motion of a radar antenna over a target region to simulate a large antenna aperture, thereby achieving high-resolution imaging capabilities. Unlike conventional radar systems, SAR synthesizes the aperture by coherently processing the backscattered signals received at different positions along the flight path, effectively creating a virtual antenna much larger than the physical one (Enyejo et al 2024). This technique allows for fine spatial resolution independent of the actual antenna size, making it particularly useful for Earth observation applications. Curlander and McDonough (1991) provide a comprehensive overview of SAR systems, detailing the signal processing techniques that enable the formation of high-resolution images from the collected radar data.

The fundamental operation of SAR involves transmitting microwave pulses toward the Earth's surface and recording the reflected signals. By analyzing the time delay and phase shift of these echoes, SAR systems can construct detailed images of the terrain. The ability to operate in all weather conditions and during both day and night makes SAR an invaluable tool for continuous environmental monitoring. Bamler and Hartl (1998) discuss the principles of SAR interferometry, an extension of SAR that exploits the phase information of the radar signals to measure surface topography and deformation with high precision. This capability is crucial for applications such as flood monitoring, land subsidence detection, and glacier movement analysis as represented in Table 1. The integration of SAR data into environmental studies enhances our understanding of dynamic Earth processes and supports effective decision-making in resource management and disaster response.

Table 1 Core Principles, Mechanisms, and Applications of Synthetic Aperture Radar (SAR)

Key Concept	Mechanisms	Applications	Advantages
Synthetic Aperture Simulation	SAR simulates a large antenna by combining backscattered signals along a flight path	Virtual aperture creation for high-resolution Earth observation.	Enables compact radar systems with extended capabilities.
High-Resolution Imaging	Spatial resolution is enhanced independently of antenna size through coherent signal processing	Capturing detailed terrain features for mapping and monitoring	Improves image clarity and feature detection
Microwave Pulse Transmission	Microwave pulses are transmitted to Earth's surface, and echoes are recorded for analysis.	Constructing terrain images under all weather and lighting conditions.	Supports continuous data acquisition in adverse conditions
SAR Interferometry	Phase differences in repeated SAR signals are analyzed to detect elevation and deformation.	Monitoring land subsidence, glacier movement, and flooding	Delivers high-precision measurements of surface changes over time.

➢ *Advantages over Traditional Optical Remote Sensing*

Synthetic Aperture Radar (SAR) offers significant advantages over traditional optical remote sensing, particularly in the context of wetland monitoring and flood detection. One of the primary benefits of SAR is its ability to operate independently of solar illumination and atmospheric conditions, allowing for consistent data acquisition during both day and night, as well as through cloud cover and precipitation (Igba et al., 2025). This capability is crucial for monitoring wetlands, which are often located in regions with frequent cloud cover and experience rapid hydrological changes as shown in Figure 1 . Adeli, et al., (2020) demonstrated the efficacy of RADARSAT-2 polarimetric SAR data in monitoring wetland water levels, highlighting its potential for providing timely and reliable information in conditions where optical sensors may fail.

Furthermore, SAR's longer wavelengths enable penetration through vegetation canopies, allowing for the detection of surface water beneath forested areas—a task that is challenging for optical sensors due to canopy obstruction. Hess et al. (1990) reviewed the capability of radar systems to detect flooding beneath forest canopies, emphasizing SAR's unique advantage in capturing inundation events that are otherwise concealed in optical imagery. This attribute is particularly important for accurate flood mapping and wetland delineation in densely vegetated regions. By providing consistent, all-weather, and canopy-penetrating observations, SAR enhances the monitoring of dynamic wetland environments, offering a robust tool for environmental management and conservation efforts.

Figure 1 showcases five distinct wetland types—(a) bog, (b) fen, (c) marsh, (d) swamp, and (e) open water wetland—each characterized by unique hydrological and vegetative features. This visual diversity highlights the challenges optical sensors face when monitoring such ecologically complex environments. Traditional optical methods are hindered by vegetation density, cloud cover, and varying light conditions, which impair their ability to detect subtle hydrological changes across these landscapes. For instance, dense tree canopies in the swamp (d) and floating vegetation in the open water wetland (e) can obscure surface water visibility. In contrast, Synthetic Aperture Radar (SAR) can penetrate through vegetative cover and is unaffected by atmospheric opacity, enabling consistent detection of water

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levels and flood events in vegetated (d) and open (e) wetland settings alike. The SAR's backscatter sensitivity to moisture levels further allows it to differentiate between the peat-rich bog (a) and sedge-dominated fen (b), capturing the fine-scale inundation dynamics essential for flood forecasting and ecological monitoring. This Figure exemplifies the wide range of wetland conditions where SAR outperforms optical systems, providing a reliable, high-resolution, and all-weather solution for environmental assessment and conservation planning.

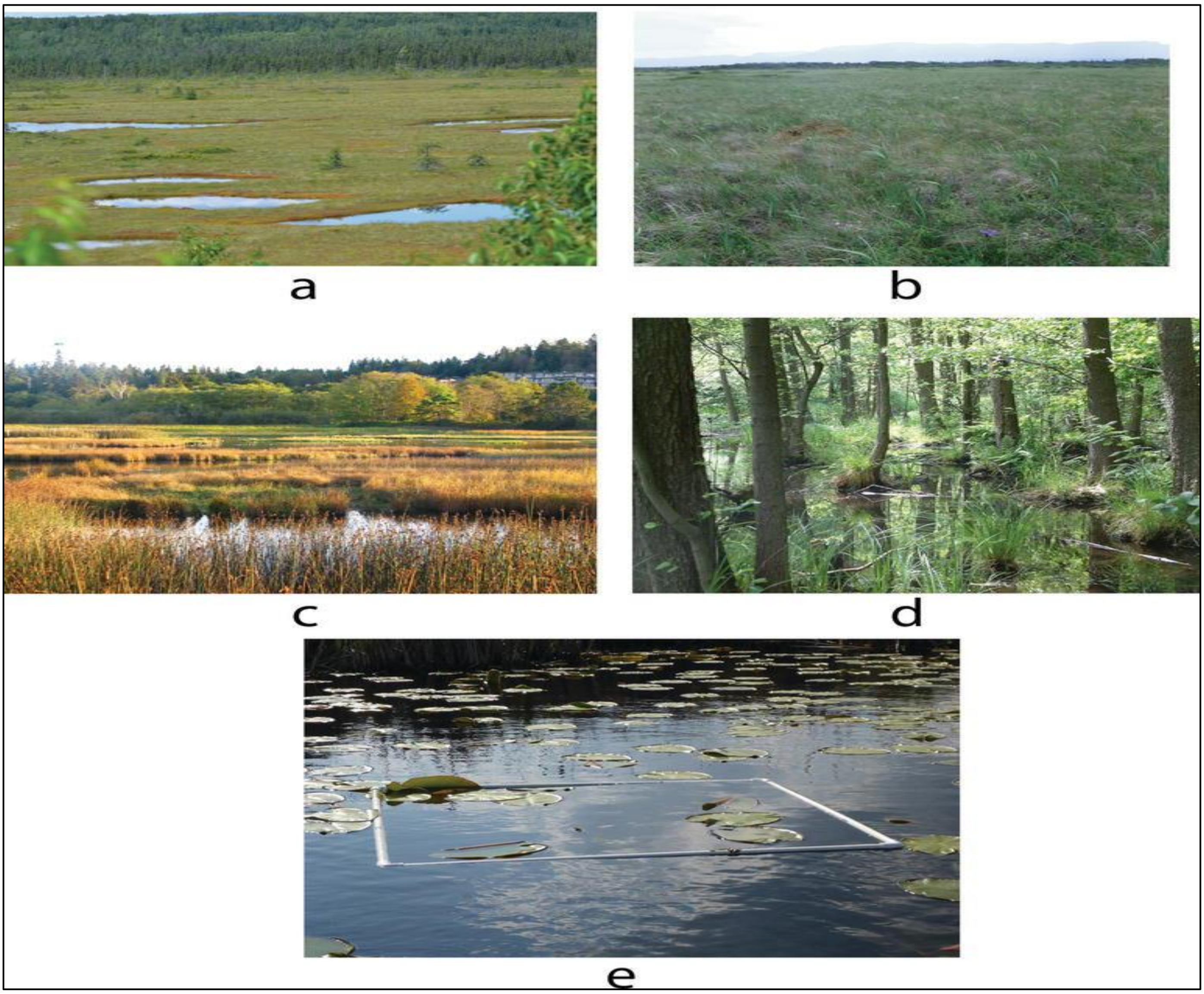

Fig 1 A Picture Showing the Diverse Wetland Types Illustrating the Monitoring Challenges Overcome by Synthetic Aperture Radar (SAR) (Dabboor, & Brisco, 2018).

- *Frequency Bands and Spatial-Temporal Resolution*

Synthetic Aperture Radar (SAR) systems operate across various frequency bands, each offering distinct advantages for wetland monitoring. The commonly utilized bands include X-band (~3 cm wavelength), C-band (~5.6 cm), and L-band (~24 cm). X-band sensors, such as TerraSAR-X, provide high spatial resolution, making them suitable for detecting fine-scale features in wetlands. However, their shorter wavelengths result in limited penetration through dense vegetation canopies. C-band sensors, like Sentinel-1, offer a balance between resolution and penetration capabilities, making them effective for monitoring moderate vegetation cover. L-band sensors, exemplified by ALOS-2, possess longer wavelengths that enable deeper penetration through vegetation, facilitating the detection of inundation beneath forest canopies (Amani et al., 2020

The spatial resolution of SAR imagery is influenced by the sensor's frequency and the system's design. Higher frequency bands typically yield finer spatial resolution, essential for detailed wetland mapping. Temporal resolution, defined by the revisit frequency of the satellite, is crucial for capturing dynamic hydrological changes in wetlands. For instance, Sentinel-1's 6–12-day revisit cycle allows for the monitoring of rapid flood events, while ALOS-2's longer revisit interval may limit its effectiveness in capturing short-term changes (Wohlfart et al., 2018). Integrating data from multiple SAR sensors operating at different frequencies can enhance both spatial and temporal resolution, providing a

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comprehensive understanding of wetland dynamics. Such integration is vital for effective wetland management and the conservation of migratory bird habitats, which are sensitive to changes in inundation patterns and vegetation structure (Idowu et al 2024).

➢ *Challenges and Limitations in SAR Data Interpretation*

While Synthetic Aperture Radar (SAR) offers significant advantages for environmental monitoring, its data interpretation presents several challenges. One primary issue is the presence of speckle noise, an inherent granular interference that arises due to the coherent nature of SAR signal processing. This noise complicates the extraction of meaningful information, particularly in heterogeneous environments like urban wetlands. Zhao et al. (2024) emphasize that speckle noise can obscure critical features in flood mapping, necessitating advanced filtering techniques to enhance image clarity. Additionally, SAR data often require complex preprocessing steps, including radiometric calibration, geometric correction, and terrain normalization, which demand specialized expertise and computational resources.

Another significant limitation is the difficulty in interpreting SAR imagery due to its unique electromagnetic characteristics. Unlike optical images, SAR data represent backscatter intensity, which varies with surface roughness, moisture content, and dielectric properties as shown in Figure 2 (Ijiga et al., 2024). This complexity can lead to ambiguities in distinguishing between different land cover types. Huang et al. (2024) discuss how generative artificial intelligence (AI) models are being explored to address these interpretation challenges by learning complex patterns within SAR data. However, the integration of AI introduces its own set of challenges, including the need for large, annotated datasets and the risk of overfitting models to specific scenarios. These limitations highlight the necessity for continued research and development to improve SAR data interpretation, particularly for applications in wetland monitoring and migratory bird habitat management.

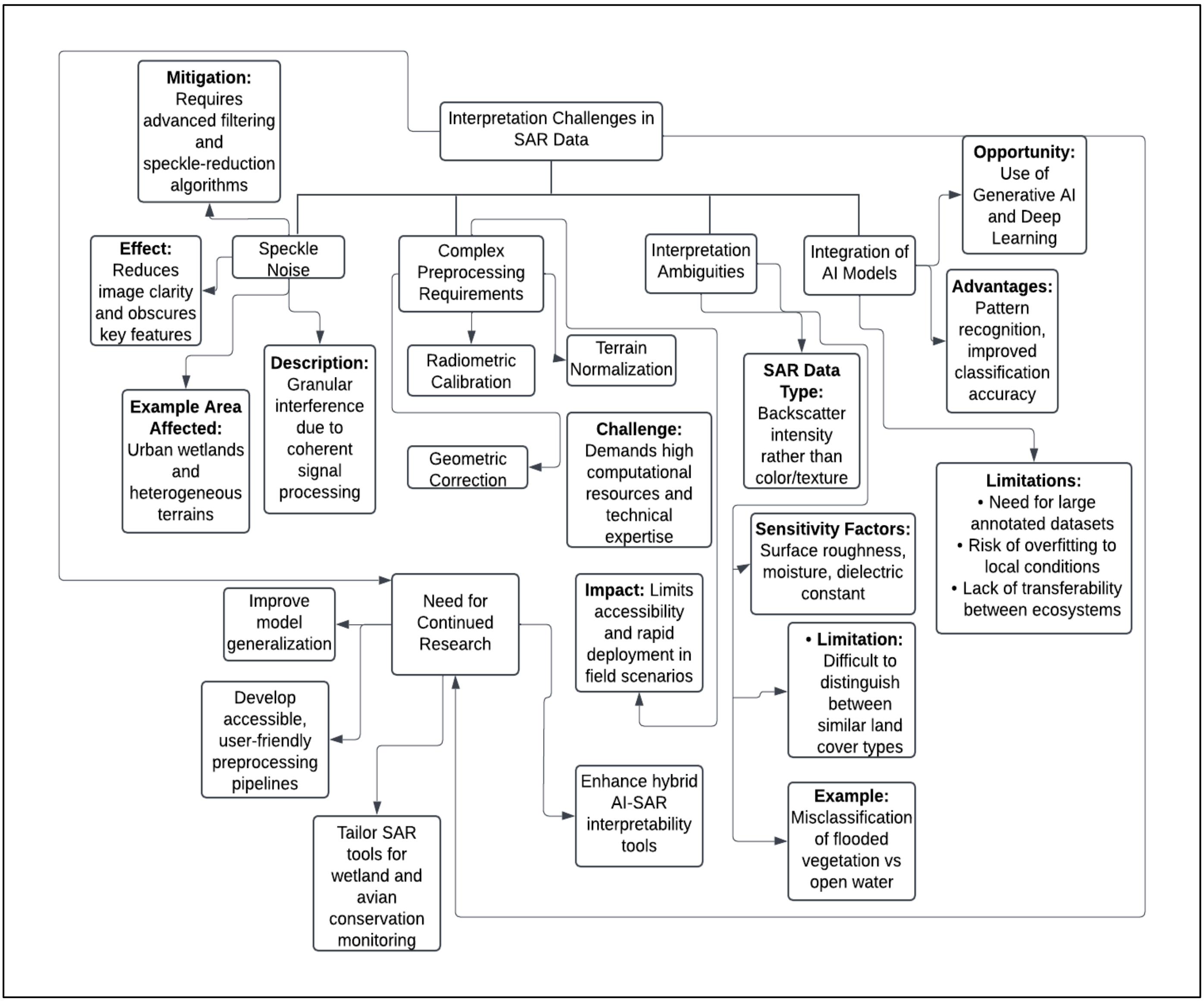

Fig 2 Block Diagram Illustrating the Technical Challenges and Emerging Solutions in Interpreting SAR Data for Wetland Monitoring

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Figure 2 presents a structured overview of the key technical and analytical barriers encountered when using Synthetic Aperture Radar (SAR) in ecological applications. At the center is the overarching challenge of SAR data interpretation, branching into four primary limitations. First is speckle noise, a granular interference that degrades image clarity, especially in heterogeneous environments like urban wetlands. Second, the complex preprocessing requirements—including radiometric calibration, geometric correction, and terrain normalization—demand specialized expertise and computational resources, limiting operational efficiency. Third, interpretation ambiguities arise due to the unique backscatter-based imagery, where surface roughness, moisture, and dielectric properties complicate land cover differentiation. Lastly, while AI integration offers promising improvements in classification accuracy through pattern recognition, it introduces new challenges such as the need for large, annotated datasets and risks of model overfitting. Together, these limitations highlight the urgent need for continued research to develop more intuitive, efficient, and transferable SAR interpretation frameworks, particularly for dynamic ecosystems like wetlands where accurate monitoring is essential for effective conservation.

III. SAR-BASED FLOOD DETECTION IN WETLAND ECOSYSTEMS

➢ *Methodologies for Flood Mapping Using SAR Imagery*

Flood mapping utilizing Synthetic Aperture Radar (SAR) imagery has become an indispensable tool in hydrological studies due to SAR's capability to penetrate cloud cover and operate under all weather conditions. The methodologies for flood detection using SAR data primarily involve change detection techniques, thresholding methods, and advanced machine learning algorithms. Change detection approaches compare pre- and post-flood SAR images to identify variations in backscatter intensity, which often indicate inundated areas (Uzoma et al., 2025). Thresholding methods, on the other hand, classify pixels based on backscatter values, distinguishing between water and non-water surfaces. Giustarini, et al. (2016) highlights the efficacy of these methods, noting that while thresholding is computationally efficient, it may require calibration for different land cover types and SAR configurations.

Recent advancements have seen the integration of machine learning techniques, such as support vector machines and convolutional neural networks, to enhance classification accuracy. These algorithms can learn complex patterns in SAR data, improving the delineation of flood extents, especially in heterogeneous landscapes. Furthermore, the incorporation of ancillary data, such as digital elevation models and land cover maps, has been shown to refine flood mapping outputs by providing contextual information that aids in the discrimination of flooded areas. Li et al. (2023) emphasizes that the synergy between SAR data and supplementary datasets significantly enhances the reliability of flood maps, which is crucial for effective disaster response and water resource management.

➢ *Case Studies on SAR Flood Detection in Global Wetlands*

Synthetic Aperture Radar (SAR) has been instrumental in flood detection across diverse wetland ecosystems globally. In the United States, SAR data have been extensively used to monitor wetlands in regions like southern Florida and Louisiana, providing critical insights into flood dynamics and wetland health. Adeli et al. (2020) conducted a comprehensive meta-analysis of SAR applications in wetland monitoring, highlighting the increasing integration of C- and L-band SAR data for improved classification accuracy in flood detection. Their study highlights the effectiveness of multi-frequency and multi-polarized SAR configurations in capturing the complex hydrological patterns of wetlands.

In Europe, the development of automated SAR-based flood services has enhanced rapid response capabilities. Martinis et al. (2015) introduced a fully automated flood mapping service using TerraSAR-X data, demonstrating its application in various flood events across Germany. The system employs a combination of radiometric thresholding and region-growing algorithms to delineate flood extents accurately. This approach has proven effective in providing timely flood maps, which are crucial for emergency management and mitigation strategies as presented in Table 2. The success of such automated systems illustrates the potential of SAR technology in operational flood monitoring, particularly in data-scarce regions where rapid information dissemination is vital (Ijiga, et al 2024).

Table 2 Automated SAR-Based Flood Mapping for Rapid Response in European Wetlands

Region/Study	SAR Technology Used	Key Contributions	Impact/Application
United States (Florida & Louisiana)	C- and L-band SAR	Monitoring wetland flood dynamics and ecosystem health	Supports conservation and hydrological modeling
Adeli et al. (2020)	Multi-frequency and multi-polarized SAR	Meta-analysis confirming improved flood detection accuracy using SAR data	Promotes SAR integration into wetland classification systems
Europe (Germany)	TerraSAR-X	Flood mapping during European events with high spatial precision	Enables timely flood response and planning
Martinis et al. (2015)	Automated SAR flood service with radiometric thresholding	Developed rapid-response flood delineation system using SAR algorithms	Improves operational flood monitoring in data-limited settings

➢ *Validation Techniques and Performance Accuracy*

Accurate flood mapping using Synthetic Aperture Radar (SAR) imagery necessitates robust validation protocols to assess performance accuracy and ensure the reliability of classification outcomes. Typically, validation involves comparing SAR-derived flood maps with ground-truth data

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or high-resolution optical imagery, when available. The use of confusion matrices is standard practice in performance assessment, from which key metrics such as overall accuracy, producer's and user's accuracy, and the Kappa coefficient are derived. These metrics help evaluate classification reliability and potential misclassifications due to terrain heterogeneity or sensor limitations (Igba et al 2024).

Pulvirenti et al. (2011) demonstrated a structured validation framework using COSMO-SkyMed SAR data, applying segmentation-based classification followed by accuracy assessment using field survey data and aerial photographs. Their study reported an overall accuracy exceeding 85%, illustrating the reliability of SAR in flood detection even under dense vegetation and complex land cover conditions. Importantly, the authors noted the necessity of integrating ancillary datasets—such as digital elevation models (DEMs)—to improve the accuracy of water extent delineation, particularly in regions where topography affects radar backscatter. The study also emphasized the importance of multi-temporal imagery, which enhances validation robustness by accounting for dynamic hydrological changes across time. These validation approaches ensure that SAR-based flood monitoring systems are dependable tools for decision-making in wetland conservation and disaster management.

➢ *Seasonal and Long-Term Wetland Hydrology Analysis*

Understanding seasonal and long-term hydrological dynamics in wetlands is essential for effective flood prediction and habitat conservation. Ijiga et al., (2024) Seasonal hydrology determines the timing and extent of inundation, influencing vegetation succession, soil moisture, and the availability of foraging grounds for migratory birds. Long-term analysis provides insights into climate-driven trends such as reduced recharge, altered hydroperiods, or wetland desiccation. SAR imagery, particularly when collected over extended periods, facilitates spatiotemporal analysis by detecting changes in surface water distribution that are otherwise unobservable via field methods.

Rebelo et al. (2010) emphasized the significance of seasonal water cycles in sustaining rural livelihoods in sub-Saharan wetlands, where variations in hydrology affect food security and biodiversity conservation. By combining multi-temporal SAR data with hydrological modeling, researchers can quantify inundation patterns across wet and dry seasons, thereby informing adaptive land-use practices as shown in Figure 3.

On a global scale, Papa et al. (2010) used a decade-long time series of passive microwave and radar datasets to assess interannual surface water variability, confirming a strong correlation between wetland dynamics and large-scale climatic phenomena like ENSO. Their findings highlight the role of SAR in revealing persistent shifts in hydrological regimes, which are critical for predicting wetland resilience and guiding long-term conservation interventions. These methodologies are pivotal for managing seasonal wetland systems under increasing anthropogenic and climate stressors.

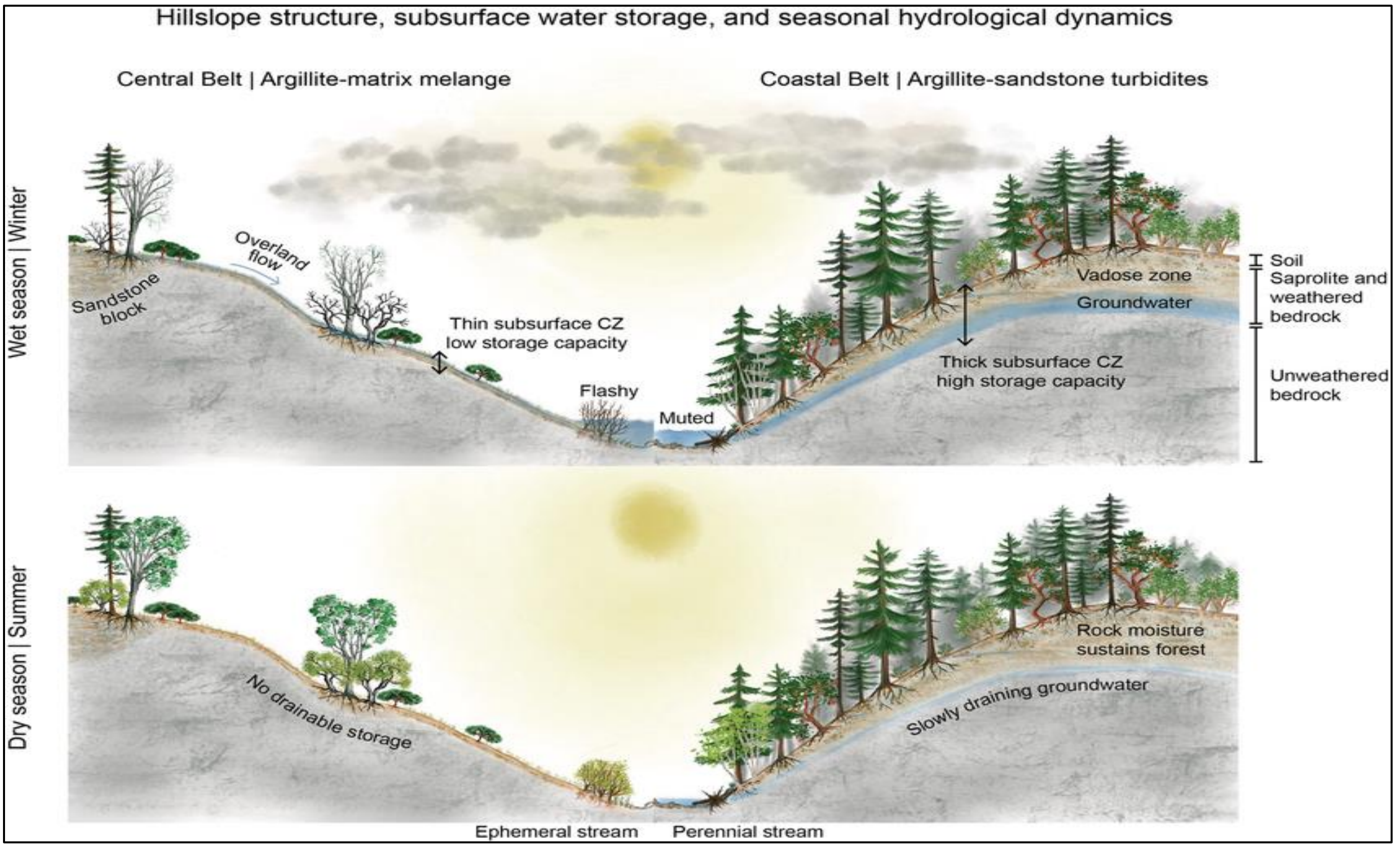

Fig 3 A Picture Showing Seasonal Hydrological Dynamics and Subsurface Storage Influences on Wetland Flow Regimes (Dralle, et al., 2023)

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Figure 3 illustrates seasonal hydrological dynamics across two contrasting hillslope structures Central Belt and Coastal Belt highlighting differences in water storage and flow between wet and dry seasons. It demonstrates how thin critical zones in the Central Belt led to rapid runoff and ephemeral streams during the wet season, followed by complete drainage and dry conditions in summer. Conversely, the Coastal Belt, with its thicker subsurface storage and vadose zone, supports muted runoff, sustained groundwater flow, and perennial streams year-round. These seasonal contrasts directly influence downstream wetland hydrology, determining the extent, duration, and frequency of inundation critical for habitat stability. SAR imagery, especially when used in long-term time series, can effectively monitor such shifts in subsurface moisture, surface water presence, and stream persistence key indicators for assessing climate-driven changes, wetland resilience, and the availability of habitat for migratory species.

IV. FLOODING IMPACTS ON MIGRATORY BIRD HABITATS

➢ *Ecological Importance of Wetlands for Migratory Birds*

Wetlands are critical ecological assets that serve as indispensable habitats for migratory bird species throughout their annual cycles. These ecosystems provide vital stopover sites for rest, feeding, and breeding, especially during long-distance migrations where energy replenishment is essential for survival. The availability, distribution, and quality of wetlands directly influence migratory routes, population dynamics, and species survival, particularly for waterfowl and waders that depend on ephemeral wetland systems.

Finlayson and Spiers (2018) highlight that wetlands support over 50% of migratory bird species globally by offering diverse hydrological and ecological niches that meet the specific needs of different avian taxa. Seasonal wetlands are especially significant for supporting pulse-dependent foraging behavior, where birds exploit brief periods of high biological productivity. In arid and semi-arid regions, migratory birds rely on wetlands as ecological refuges that provide consistent moisture and food resources during otherwise inhospitable dry seasons.

However, wetland loss and hydrological alteration due to anthropogenic pressures pose a serious threat to these migratory networks. The functional connectivity among wetlands is essential for enabling uninterrupted migration, making conservation of both large-scale wetland complexes and smaller satellite sites critical. Remote sensing tools like SAR are pivotal in monitoring these dynamic habitats, ensuring timely conservation interventions that preserve the ecological integrity required for sustaining migratory bird populations.

➢ *Effects of Flooding on Breeding and Foraging Grounds*

Flooding events in wetland ecosystems play a complex role in shaping the breeding and foraging opportunities available to migratory birds. While moderate inundation can enhance habitat quality by stimulating invertebrate and vegetation growth, excessive or untimely flooding disrupts reproductive success and food access (Ijiga et al, 2024). Seasonal breeding grounds, particularly those in agricultural floodplains or shallow marshes, are vulnerable to over-inundation during nesting periods, leading to nest abandonment or egg loss.

Stralberg et al. (2020) assessed flood-related breeding risks for waterbirds in California's Central Valley and found that early-season flooding, driven by climate-induced hydrological shifts, inundated key nesting habitats for species such as the Black-necked Stilt and American Avocet. These disruptions reduced reproductive output and altered spatial nesting distributions, forcing birds to seek suboptimal or degraded sites.

Foraging grounds are similarly affected by flood dynamics. Ntiamoa-Baidu et al. (2008) observed that waterbird species in Ghana's coastal lagoons adjusted their foraging strategies based on fluctuating water depths, with both prey availability and foraging efficiency heavily influenced by hydrological conditions. Extended or deep inundation reduced prey accessibility for tactile feeders, undermining the energy balance required during migration stopovers as shown in Figure 4. Understanding these ecological dependencies is essential for designing adaptive wetland management strategies that accommodate the nuanced effects of flooding on avian breeding and foraging ecology.

Figure 4 shows a vulnerable chick nestled in semi-submerged vegetation within a flooded wetland environment, symbolizing the delicate balance between hydrological conditions and avian reproductive success. This scenario reflects how excessive or poorly timed inundation can compromise nesting habitats for migratory birds. While some flooding promotes invertebrate abundance beneficial for chick development, persistent high-water levels—such as those visible here—may isolate nests, displace fledglings, or increase exposure to predators. For tactile foragers, deep water further hinders access to food, reducing energy intake during critical life stages. This image exemplifies the ecological risk posed by altered flood regimes, reinforcing the need for seasonal water management strategies that ensure breeding habitats remain accessible and secure during peak nesting periods. Such interventions are crucial to sustaining healthy bird populations in dynamic wetland ecosystems.

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Fig 4 A Picture Showing Flooded Nesting Grounds and the Vulnerability of Wetland Birds (Woodburn, 2023)

- *SAR-Based Identification of Habitat Shifts and Degradation*

The identification of habitat shifts and degradation through Synthetic Aperture Radar (SAR) technology offers a vital means of tracking wetland dynamics and their impact on migratory bird populations. SAR systems, owing to their ability to detect surface structure changes under all weather conditions, enable consistent monitoring of wetland inundation patterns, vegetation cover, and soil moisture—key indicators of habitat quality and transformation. When combined with time-series analyses, SAR data can reveal both gradual and abrupt ecological changes driven by hydrological disturbances, land conversion, or climate extremes (Ijiga et al., 2024).

Ayat et al. (2021) demonstrated the capacity of Sentinel-1 SAR data to monitor habitat loss in African ecosystems, with a focus on changes in landscape structure relevant to large mammal habitats. The methodologies applied—particularly backscatter analysis and coherence-based change detection—are equally adaptable to wetland environments. These techniques can quantify vegetation degradation and surface water loss, which directly affect foraging and nesting areas used by migratory birds. For instance, reduced radar backscatter over time may indicate increased soil dryness or vegetation dieback, signaling ecological stress or wetland desiccation. SAR's sensitivity to vertical structure also allows detection of marsh encroachment, which may hinder avian access to shallow feeding zones. Consequently, SAR facilitates the proactive identification of at-risk habitats, supporting targeted conservation interventions.

- *Species-specific Case Studies and Conservation Implications*

Species-specific case studies offer critical insight into conservation planning, especially when evaluating habitat degradation caused by climate extremes and anthropogenic activities. For example, Runge et al. (2015) highlighted the vulnerability of long-distance migratory birds such as the bar-tailed godwit (Limosa lapponica), which rely on a chain of protected stopover habitats for survival. Their modeling demonstrated that even small disruptions in these interconnected nodes—due to flooding, sea-level rise, or land conversion—can lead to catastrophic population declines. This highlights the importance of spatially coordinated conservation strategies that consider full migratory pathways rather than isolated reserves.

Similarly, Mantyka-Pringle et al. (2012) provided meta-analytic evidence that the interaction between habitat fragmentation and climate-induced stressors disproportionately affects range-restricted amphibians and reptiles. For instance, the northern corroboree frog (Pseudophryne pengilleyi) experiences heightened extinction risk due to the compounded effects of reduced breeding sites and shifting temperature gradients. Conservation implications from such findings stress the need for dynamic, species-tailored interventions that integrate habitat restoration with climate resilience frameworks as presented in Table 3. Additionally, predictive modeling based on species' ecological niches can support prioritization of critical zones for conservation funding and legislative protection (Enyejo, et al., 2024). These case studies reinforce that high-resolution, species-focused research is indispensable in mitigating biodiversity loss under increasing environmental volatility.

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Table 3 Species-Specific Vulnerabilities and Strategic Conservation Responses in Wetland Ecosystems

Species/Study Focus	Stressors Identified	Conservation Insight	Management Implications
Bar-tailed Godwit (Limosa lapponica)	Flooding, sea-level rise, habitat loss	Migratory success depends on intact habitat networks	Protect and connect critical stopover zones
Northern Corroboree Frog (Pseudophryne pengilleyi)	Habitat fragmentation, temperature shifts	Species with narrow ranges face disproportionate risks	Prioritize range-restricted species for targeted actions
Runge et al. (2015)	Disruption in migratory stopover sites	Conservation must be spatially coordinated along migratory routes	Use predictive modeling to guide resource allocation
Mantyka-Pringle et al. (2012)	Climate-induced stress compounded by habitat degradation	Calls for integration of climate resilience in habitat restoration	Develop dynamic, species-specific adaptation strategies

V. INTEGRATING SAR DATA INTO HABITAT MANAGEMENT

➢ *Role of SAR in Adaptive Wetland Management Practices*

Synthetic Aperture Radar (SAR) has emerged as a transformative tool in adaptive wetland management due to its ability to capture high-resolution, all-weather, and day-night imagery of dynamic hydrological systems. Jung et al. (2020) emphasized the utility of SAR in generating temporally consistent, spatially detailed wetland maps, which are critical for informing policy decisions and ecological restoration. Their global-scale analysis demonstrated that SAR-based datasets accurately delineate flood pulse regimes and intra-annual water extent variations, enabling managers to identify seasonal inundation thresholds and shifts in wetland connectivity.

In adaptive management frameworks, where iterative decision-making depends on continuous environmental feedback, SAR facilitates near-real-time monitoring of hydrological changes resulting from climate anomalies or anthropogenic interference. For instance, SAR time-series have been effectively applied to assess post-storm wetland recovery trajectories and to monitor sediment redistribution in deltaic regions—parameters often missed by optical sensors due to persistent cloud cover. Furthermore, SAR-derived coherence and backscatter metrics provide quantitative measures of vegetation structure and water saturation levels, enabling ecosystem managers to evaluate the efficacy of water retention or diversion interventions (Ijiga et al, 2024).

By integrating SAR data into hydrological models and ecosystem service assessments, stakeholders can refine water allocation schedules, restore functional hydrology, and mitigate biodiversity loss under uncertain climate futures as presented in Table 4. The continuous, reliable monitoring capacity of SAR systems positions them as indispensable components in data-driven wetland governance.

Table 4 SAR in Adaptive Wetland Management

Key Concept	SAR Application	Impact on Wetland Management	Implications for Governance
All-Weather and Day-Night Monitoring	SAR provides continuous monitoring across different weather conditions and times of day.	Enables continuous and consistent monitoring of dynamic wetland systems.	SAR data allows for reliable, data-driven decision-making under uncertain environmental conditions.
Seasonal Inundation and Connectivity	SAR captures temporal changes in water extent and delineates flood pulse regimes.	Helps identify shifts in wetland connectivity, informing adaptive management decisions.	SAR enhances ecological restoration and policy decisions by refining wetland flood regime mapping.
Real-Time Environmental Feedback	SAR time-series are used for post-storm recovery analysis and monitoring hydrological changes.	Supports adaptive frameworks by providing real-time data for iterative decision-making.	Facilitates the monitoring of post-climate anomalies and human-induced hydrological changes.
Quantitative Vegetation and Water Assessment	SAR metrics such as coherence and backscatter assess vegetation structure and water saturation.	Improves understanding of water retention and diversion effectiveness, guiding interventions.	SAR integration into models allows for better water allocation, functional hydrology restoration, and biodiversity conservation.

➢ *Data-Driven Early Warning Systems and Policy Frameworks*

The integration of data-driven early warning systems into environmental governance has significantly enhanced the anticipatory management of flood-prone and ecologically sensitive regions. Pulwarty and Sivakumar (2014) emphasize that robust early warning systems must be underpinned by multi-source data assimilation, including satellite remote sensing, in-situ hydrological observations, and real-time climate forecasts. Such systems support adaptive policymaking by providing probabilistic alerts that trigger preemptive measures at local and regional levels, minimizing socio-ecological disruptions. In the context of wetland management, these alerts help precondition policy

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frameworks for dynamic response strategies, such as wetland buffer reconfiguration and pre-flood evacuations.

Hauduc, et al. (2015) extend this discourse by outlining the structural underpinnings of effective hydrologic early warning systems, particularly the need for modular, open-data platforms that enable cross-sector interoperability. Their analysis points to the importance of coupling streamflow simulation models with meteorological prediction systems to enhance the spatial and temporal resolution of flood forecasts. Furthermore, policy alignment is achieved when these systems are embedded within institutional protocols, including environmental impact assessments and risk governance frameworks. For example, automated thresholds derived from SAR and rainfall analytics can activate wetland watergate controls, reinforcing conservation and resilience objectives. These frameworks ensure that data-driven early warning systems serve as both technical safeguards and catalysts for proactive environmental legislation.

➢ *Community-Based Monitoring and Stakeholder Engagement*

Community-based monitoring (CBM) and inclusive stakeholder engagement are vital mechanisms for integrating local knowledge into adaptive wetland management. Danielsen et al. (2010) argue that CBM systems, when designed with meaningful community involvement, can achieve faster implementation and broader spatial coverage than top-down monitoring frameworks. In flood-prone wetland areas, local residents are often the first to observe hydrological changes such as altered floodplain flow, vegetation shifts, or sediment deposition. Integrating these observations through mobile platforms or standardized data sheets enables real-time inputs into early warning systems and contributes to a more granular understanding of ecological dynamics (Ijiga et al., 2024).

Reed (2008) emphasizes that stakeholder participation must move beyond tokenistic consultation toward co-management, where diverse actors—ranging from indigenous groups to civil engineers—contribute to decision-making processes. For instance, participatory scenario modeling exercises that involve farmers, conservationists, and government officials have been successful in aligning water-use policies with ecosystem thresholds. Such engagement not only improves the legitimacy and acceptability of management decisions but also facilitates long-term stewardship and resilience as shown in Figure 5. Effective stakeholder engagement also supports social learning, wherein trust-building and knowledge exchange enhance adaptive capacity at the community level. When paired with SAR-based data and institutional tools, community-driven approaches ensure that wetland governance remains both scientifically grounded and socially responsive.

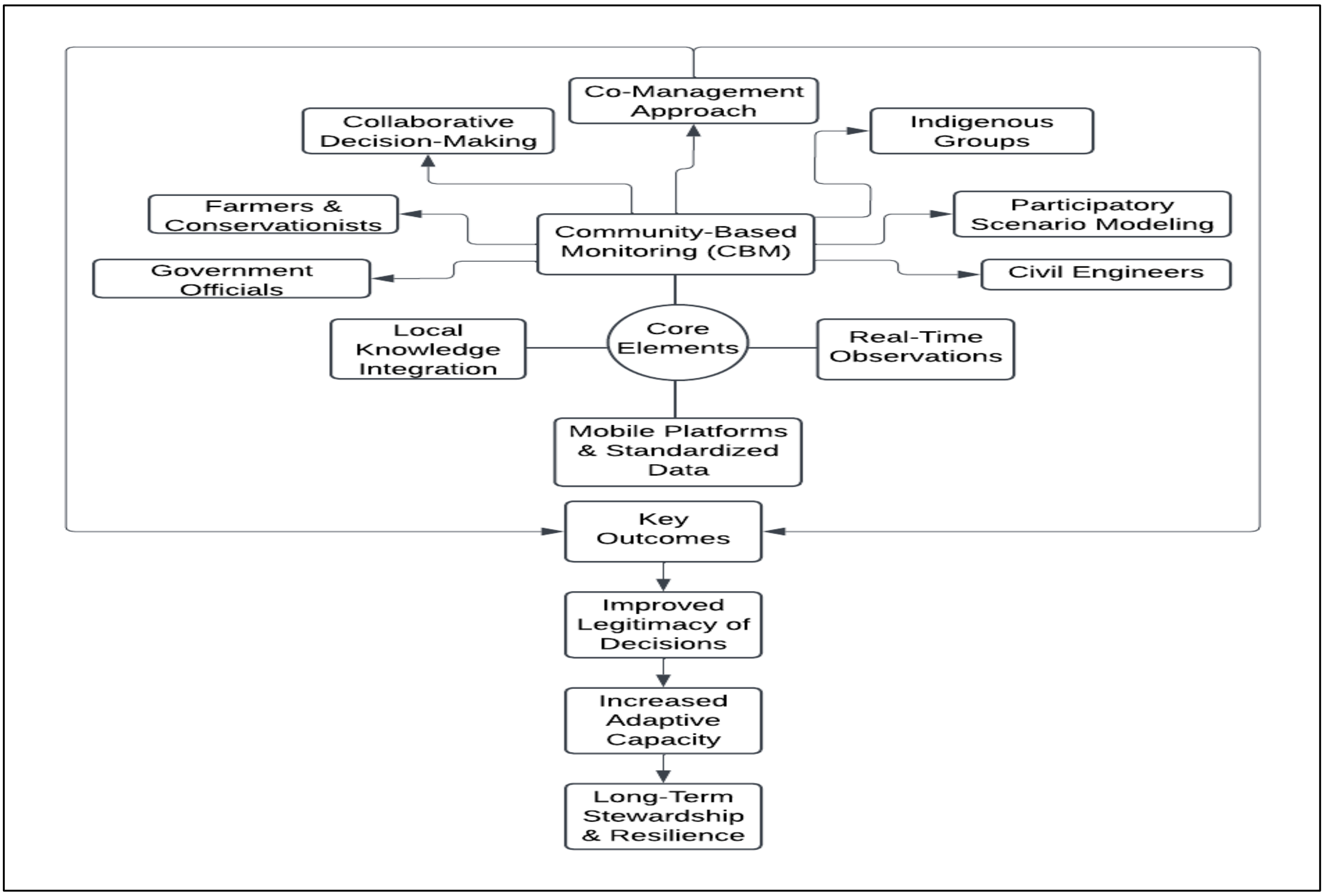

Fig 5 Block Diagram Illustrating the Integrating Community Knowledge and Stakeholder Collaboration for Adaptive Wetland Governance

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Figure 5 illustrates how community-based monitoring (CBM) and stakeholder collaboration are integral to effective wetland management. At the center, CBM leverages local knowledge integration and real-time observations through mobile platforms and standardized data. These insights are complemented by external stakeholder engagement, which involves a co-management approach with diverse groups such as indigenous communities, civil engineers, government officials, farmers, and conservationists. This collaborative decision-making process, enhanced by participatory scenario modeling, ensures inclusive, adaptive strategies. Ultimately, the diagram shows that these efforts result in improved legitimacy of decisions, increased adaptive capacity, and long-term stewardship and resilience of wetland ecosystems. The integration of SAR-based data further supports informed, data-driven governance.

VI. ADVANCEMENTS AND FUTURE DIRECTIONS

➤ *Integration of SAR with AI and Machine Learning*

The integration of Synthetic Aperture Radar (SAR) data with artificial intelligence (AI) and machine learning (ML) algorithms has revolutionized the capacity for real-time wetland analysis, flood prediction, and ecosystem monitoring. According to Mohsen, et al., (2018), deep learning models—particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs)—have demonstrated superior performance in processing complex SAR backscatter data, enabling enhanced classification accuracy of water bodies, vegetation structures, and soil moisture conditions under all weather conditions. The robustness of AI-driven classification is particularly advantageous in flood-prone wetland zones, where temporal and spatial resolution of hydrological features is critical for adaptive management as shown in Figure 6.

In practice, AI-enabled systems can ingest continuous SAR time-series imagery to detect surface water changes, anomalies in inundation patterns, and even early indicators of wetland degradation. These models are often trained on large datasets that include multi-frequency SAR inputs (e.g., C-band, L-band) and ancillary data such as digital elevation models and meteorological variables. Once deployed, the systems can autonomously trigger alerts, classify land cover transitions, and prioritize zones for conservation intervention. Additionally, integration into cloud-based geospatial platforms facilitates inter-agency access and collaborative response. The synergy between SAR and AI is rapidly becoming essential for scalable, intelligent environmental monitoring frameworks that support precision decision-making in wetland management.

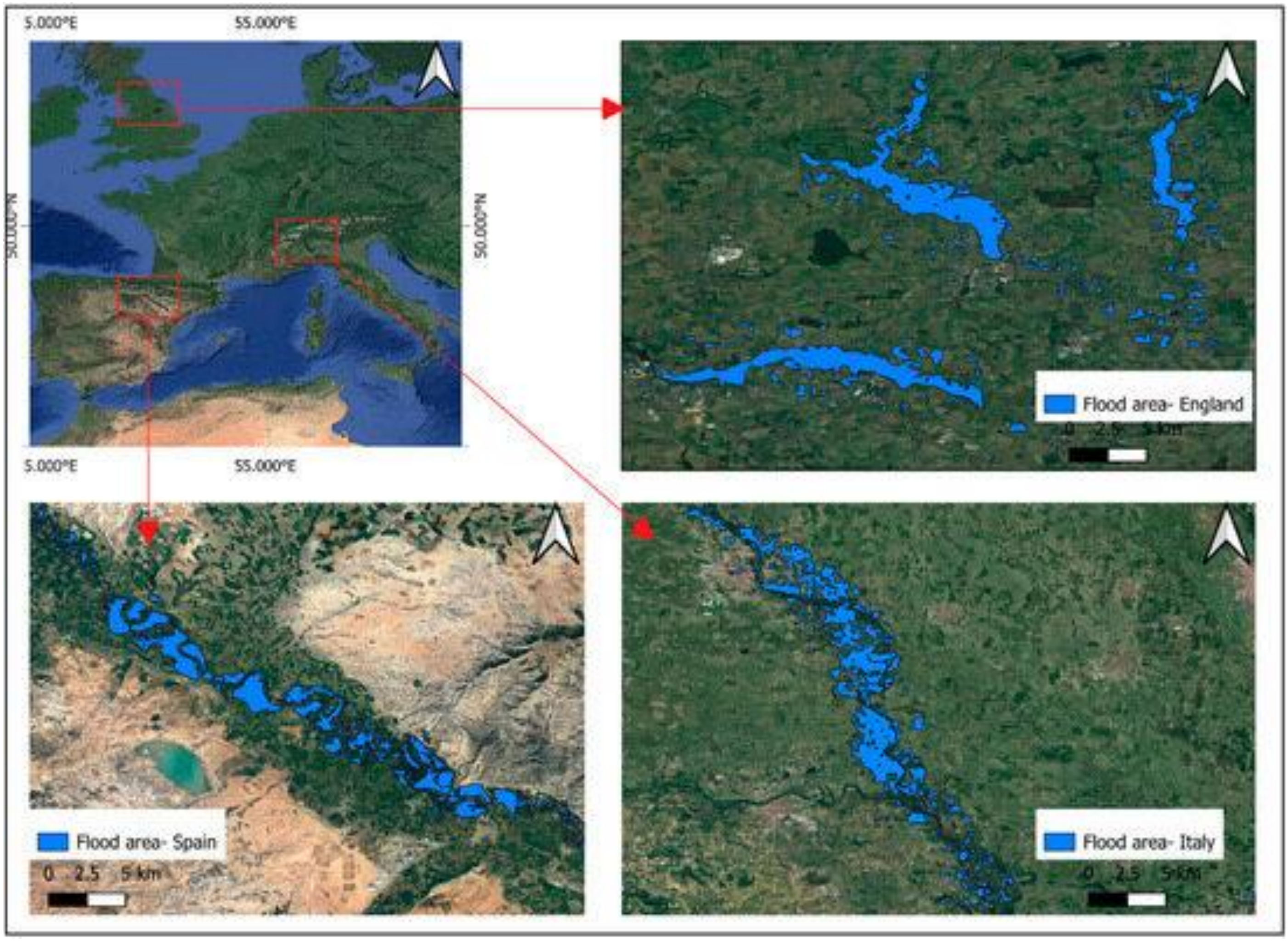

Fig 6 A Picture Showing AI-Enhanced SAR Flood Mapping Across European Wetlands (Lahsaini, et al, 2024)

Figure 6 highlights the power of combining Synthetic Aperture Radar (SAR) with AI algorithms for large-scale flood detection and analysis. SAR's all-weather imaging capability ensures consistent monitoring of surface water changes, even under cloud cover or during night conditions, which is critical during flood events. When fused with AI models such as convolutional neural networks (CNNs), as demonstrated in the generation of these flood maps, the system enhances classification accuracy by efficiently distinguishing water bodies from surrounding land cover. The consistent flood boundary extraction across multiple regions, despite varying terrain and climatic conditions, suggests the application of trained machine learning models capable of generalizing across geographic contexts. This integration not only accelerates the generation of actionable flood maps but also supports real-time decision-making for emergency response and wetland conservation. It exemplifies how AI-enhanced SAR analytics can autonomously detect hydrological anomalies, prioritize intervention zones, and contribute to scalable, data-driven environmental management.

➢ *Multi-Sensor Approaches and Satellite Constellations*

The use of multi-sensor approaches and satellite constellations significantly enhances the capacity to monitor wetland ecosystems with high spatial, temporal, and spectral resolution. Derksen, et al. (2017) emphasized the synergy of combining active sensors like Synthetic Aperture Radar (SAR) with passive microwave radiometry for global-scale soil moisture and freeze/thaw detection. This integration is particularly effective for tracking hydrological transitions in wetlands, which often occur under cloud cover or in complex terrains where optical sensors are less reliable. By leveraging complementary sensor characteristics, such as SAR's structural sensitivity and passive microwave's radiometric responsiveness, managers can achieve more accurate and temporally consistent wetland state assessments (Ijiga et al., 2025).

Roy et al. (2014) highlighted the role of satellite constellations, such as the Landsat-8 and Sentinel series, in facilitating near-continuous Earth observation. These platforms enable inter-calibrated, multi-spectral datasets that support dynamic wetland delineation, vegetation phenology monitoring, and flood mapping. When used alongside SAR imagery, these constellations provide a holistic view of surface and sub-surface hydrological processes. This integrated monitoring strategy is critical for developing predictive ecological models, validating land cover classifications, and supporting early-warning systems as presented in Table 5. By synchronizing data streams from multiple orbits and instruments, satellite constellations ensure redundancy, cross-verification, and operational continuity in environmental observation frameworks critical to wetland resilience.

Table 5 Enhancing Wetland Monitoring with Multi-Sensor Approaches and Satellite Constellations

Key Concept	Description	Applications	Benefits
Multi-Sensor Approaches	Combining active sensors like SAR with passive microwave for enhanced data accuracy.	Tracking hydrological transitions in wetlands, particularly under cloud cover.	More accurate, temporally consistent data for wetland management.
Satellite Constellations	Using satellite constellations (Landsat-8, Sentinel) for continuous Earth observation.	Enabling near-continuous, high-resolution monitoring of wetland systems.	Facilitates dynamic delineation and flood mapping.
Sensor Synergy	Leveraging complementary sensor characteristics for more accurate wetland assessments.	Improving temporal consistency in wetland state assessment.	Enhances the ability to monitor complex terrains and remote areas.
Integrated Monitoring Strategy	Fusing data from multiple sensors and satellites to create a holistic view of wetland dynamics.	Validating wetland mapping, developing predictive models, and supporting early-warning systems.	Ensures redundancy and operational continuity for environmental monitoring.

➢ *Open-Access Platforms and Cloud-Based Analysis Tools*

The emergence of open-access platforms and cloud-based analysis tools has democratized remote sensing applications in environmental monitoring, particularly for wetland conservation. Gorelick et al. (2017) presented Google Earth Engine (GEE) as a transformative platform that enables planetary-scale geospatial analysis through a cloud-based interface. GEE hosts a multi-petabyte catalog of satellite imagery, including Synthetic Aperture Radar (SAR), Landsat, MODIS, and Sentinel data, which can be analyzed without the need for local high-performance computing infrastructure. This accessibility allows conservation practitioners, researchers, and policymakers—especially in resource-limited settings—to process and visualize time-series datasets, derive flood extent maps, and monitor vegetation dynamics at scale.

In the context of wetland systems, cloud-based platforms facilitate automated change detection, hydrological modeling, and cross-temporal comparisons, which are essential for evaluating the impact of seasonal flooding, anthropogenic pressures, and climate change. GEE's programmable interface supports scalable computation using JavaScript or Python, enabling the integration of machine learning classifiers and SAR feature extraction algorithms. Moreover, its open-access ethos promotes reproducibility, collaborative workflows, and transparency in ecological research. By lowering technical and financial barriers, platforms like GEE have accelerated the translation of satellite data into actionable intelligence for wetland management, enhancing responsiveness and fostering a culture of open science within global environmental governance systems.

➢ *Future Research Needs and Interdisciplinary Pathways*

Future research in SAR-based wetland monitoring must advance toward integrating ecological, hydrological, and socio-political dimensions through transdisciplinary frameworks. Schimel et al. (2015) emphasized the need for coupling SAR observations with carbon flux models to understand wetland roles in the global carbon cycle. This demands enhanced temporal sampling and the fusion of SAR with optical and LiDAR data to quantify biomass, peatland methane emissions, and soil saturation dynamics. A research agenda that bridges biogeophysical monitoring with ecosystem service valuation will strengthen predictive capacity and conservation planning under climate uncertainty.

Polk, (2015) highlighted that addressing environmental complexity requires knowledge co-production between scientists, policymakers, and indigenous communities. Interdisciplinary research must move beyond disciplinary silos to create participatory models that integrate local knowledge, governance structures, and advanced geospatial analytics. For example, deploying AI-driven SAR interpretation tools through co-designed dashboards can enable stakeholders to collaboratively identify risk thresholds, design mitigation strategies, and evaluate policy interventions. Institutionalizing such participatory monitoring systems will enhance legitimacy, ownership, and scalability of environmental solutions. These pathways not only guide methodological innovation but also ensure that SAR technologies are embedded within socially responsive and ecologically resilient frameworks, laying the foundation for long-term wetland sustainability and adaptive policy evolution (Ijiga, et al., 2024).

VII. CONCLUSION AND RECOMMENDATIONS

➢ *Summary of Key Findings from SAR Applications*

This review highlights the robust capabilities of Synthetic Aperture Radar (SAR) in detecting and monitoring flood dynamics within wetland ecosystems. SAR's all-weather, day-and-night imaging capability, along with its sensitivity to surface moisture and structural changes, makes it a powerful tool for flood mapping, hydrological assessment, and habitat degradation analysis. The use of multi-frequency SAR data and time-series observations has enabled the detection of both rapid inundation events and long-term ecological shifts. Case studies demonstrate SAR's operational efficiency in tracking wetland changes and informing habitat suitability for migratory birds.

➢ *Implications for Wetland and Avian Conservation*

The application of SAR in wetland hydrology directly supports avian conservation by enabling the timely detection of habitat alterations that affect nesting, breeding, and foraging patterns. As migratory birds rely on predictable hydrological conditions, SAR facilitates the identification of disruptions that may impact survival. Integration of SAR-derived data into habitat models enhances the ability to prioritize conservation efforts, monitor the effectiveness of restoration projects, and ensure ecological resilience in the face of climate variability and anthropogenic pressures.

➢ *Policy and Technological Recommendations*

To optimize SAR's potential, policies must prioritize open-access satellite data, capacity building for local conservation teams, and the integration of SAR monitoring into national biodiversity strategies. Technological recommendations include adopting AI-enhanced classification methods, advancing automated flood detection platforms, and fusing SAR data with optical and ancillary datasets for enriched ecological insights. Establishing standardized protocols for SAR-based ecological assessments will further enhance data interoperability and application.

➢ *Call for Sustained Investment and Global Cooperation*

Sustained investment in SAR infrastructure, research, and cross-sector collaboration is essential to fully realize its conservation potential. Wetland ecosystems, being globally interconnected and ecologically sensitive, require coordinated monitoring efforts and funding mechanisms that transcend national boundaries. International partnerships among space agencies, conservation organizations, and policymakers must be strengthened to ensure consistent data flows, shared knowledge systems, and unified action against wetland degradation. Such global cooperation is vital for protecting migratory bird corridors and preserving the ecological functions of wetlands in an era of accelerating environmental change.

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