

Optimizing Riparian Habitat Conservation: A Spatial Approach Using Aerial and Space Technologies

Ravindra Nath Tripathi , Aishwarya Ramachandran , Vikas Tripathi, Ruchi Badola, and S. A. Hussain 

I. INTRODUCTION

Abstract—Riparian habitats are the most crucial yet the most fragile ecosystems, focal to safeguarding both the aquatic and terrestrial regions. Technology such as remote sensing, now powered by cloud-based server-side processing of high-resolution satellite imagery, and Big Data analytics, such as Google Earth Engine (GEE) combined with uncrewed aerial vehicles (UAVs), have accentuated ecological monitoring of natural habitats. This study leverages a nested approach to remote sensing, combining satellite data and UAV imagery to evaluate the present condition of riparian habitats along the Ganga River in the Upper Gangetic Plains. We used GEE to analyze Sentinel data and identify critical habitats, encompassing wetlands, grasslands, scrublands, plantations, river islands, and riparian forests in the study area. Strategic locations covering 291 km² area were delineated, and over 1000 patches of 1 ha were isolated, with the largest patch of 23.99 km² in Haiderpur. Furthermore, UAV-based data were collected for key identified regions. The status of a total of 284 field surveyed points was categorized as 29 intact grassland patches, 87 good habitat patches, 25 patches recently converted to agriculture, and 60 patches being converted to agriculture, remaining plantations, and waterbodies. UAV-based raster thematic maps of four key habitat regions generated using object-based image analysis classification found a promising approach for high-precision riparian habitat mapping, monitoring, and management, offering data quality, cost optimization, and time savings with an overall accuracy of 98% and kappa coefficient 0.97. UAV are, thus, effective tools for reach-level assessment of freshwater habitats, especially of smaller stream networks, retaining fine-scale riverscape information of the mosaic of land use and vegetation types.

Index Terms—Ecological monitoring, Ganga, Google Earth Engine (GEE), machine learning, object-based image analysis (OBIA), uncrewed aerial vehicle (UAV).

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RIPIARIAN habitats are one of the most crucial yet the most vulnerable ecosystems that protect the aquatic terrestrial zones [1], [2]. They play a vital role in nutrient cycling and maintaining water quality by filtering sediments, nutrients, and pollutants, stabilizing banks, reducing erosion, and groundwater recharge [2], [3], [4]. Riparian vegetation also plays a crucial role in regulating water temperature and microclimate, supporting aquatic life [5]. They also maintain lateral connectivity [6]. Being in the floodplain zone, they are susceptible to changing environmental conditions, such as alternating water regimes, soil moisture, substrate, gradation, and extreme events; meanwhile, they are also most resilient to climate change and buffer against floods or droughts [7]. They support a variety of vegetation ranging from aquatic plants, grasses, semiaquatic sedges, and shrubs to trees, often forming a successive belt buffering the freshwater bodies. Forming an ecotone between aquatic and terrestrial habitats, they are biodiversity-rich, often active as a refuge and dynamic corridors facilitating animal migration [8], [9], [10], [11], [12]. Hence, they foster aquatic and semiaquatic fauna and flora and are essential for terrestrial life forms. However, they are also the most sought-after ecosystems due to their fertility and availability of water. Riparian habitats, including riparian grasslands and riverine wetlands, are vulnerable to changes in the course of rivers and prone to rapid development—as agricultural lands, settlements, and industries. These riparian habitats are often underprotected compared to protected areas (PAs) and prone to high anthropogenic dependence on ecosystem services [13]. Frequently, divergent needs for the use of riparian zones, such as demands for the agricultural sector, urban growth, and conservation, may hinder decision-making and create conflicts [14]. Since river systems are constantly evolving and shifting, it is challenging to implement effective management practices. The changes in habitat occur on a seasonal basis, unlike terrestrial habitat. Rapid assessment of these habitats is required due to their dynamic nature, which is complicated by the lack of publicly available data products, free datasets, and low accuracy and resolution of existing data [2]. Adopting a multiscale studies and improving data availability have great potential in protecting these crucial habitats. Remote sensing-based satellite technologies, the global positioning system (GPS), and geographic information system provide promising tools for habitat assessment. The advancement of satellite imagery provides high-resolution imagery and has the potential to monitor and analyze the spatiotemporal extent of riparian habitats [15]. Remote sensing technology, now powered

by cloud-based server-side processing and Big Data analytics, has strengthened ecological monitoring. Despite having significant promise, freely available satellite imagery such as Landsat and Sentinel have few limitations, such as coarse resolution, cloud cover presence, and the requirement of substantial time and resources for processing extensive volumetric data [16], [17]. As a better alternative, uncrewed aerial vehicle (UAV) based remote sensing allows low-cost, high-resolution, real-time monitoring, instant data access, on-demand data collection, customizable sensors, and flexible observations [18], [19]. Furthermore, UAVs are very useful in high-resolution localized data collection where detailed assessment is required, especially for inaccessible landscapes [19], [20]. Drones, also referred to as UAVs/systems, remotely piloted aircraft, or flying robots, have transformed many industries worldwide. UAVs enable real-time monitoring in many sectors, including agricultural applications, construction surveying, captivating filming, medical supply delivery, efficient e-commerce distribution, secure mining surveying, and various other uses [21], [22], [23]. With the ease of use and constant innovation, it is incessantly growing and offering transformative solutions in habitat mapping, land surveying, and change detection. Drones are equipped with cameras and sensors to capture high-resolution aerial imagery of riparian habitats, which create detailed maps of riparian vegetation, water quality, and other environmental parameters. However, there are various issues with UAVs, such as weather dependence, limited coverage, short flight time, regulatory restrictions, and integration with global data. Despite the pros and cons of both UAVs and freely available satellite data, the fusion of drones and satellites has produced even better and practical results [24]. We have, however, utilized satellite imagery as an assistive tool to UAVs in analyzing the current status of riparian habitat in our study area. Using a multiscale approach, we have utilized satellite data to identify habitats at the riverscape level and selected important regions for conducting drone flights at the river reach level.

Ganga is significant as the National River not only because of the livelihoods it supports but also due to the biodiversity it fosters. The Upper Ganga and Upper Middle Ganga River stretches are incredibly unique owing to their geomorphology ranging from Himalayan foothills to Gangetic plains. After Rishikesh, the Ganga exits the Shiwaliks or Himalayan foothills and enters the plains near Haridwar. The study area stretches from Haridwar, Uttarakhand to Narora, Uttar Pradesh, in the Upper Gangetic Plain, comprising three river classes—Himalayan, Piedmont, and Valley interfluvial that are characterized by braided channels with sandbars, midriver alluvial islands, multiple networks, active floodplain, and changing course [25]. The riparian vegetation of this stretch comprises *Phragmites-Saccharum-Imperata* grasslands [26]. This unique stretch of the Ganga River holds immense ecological significance due to the presence of many flora and fauna, including otters, crocodiles, turtles, and Gangetic dolphins, suitable habitats with broad flood plain, midriver islands, sandy beds, meandering pools, riffles, and active breeding sites indicating good biodiversity [27]. The confluence of Ban Ganga, Solani, Choyya, and Sharda canals also add to the habitat heterogeneity, although they do not substantially add to the flow during the nonmonsoonal season.

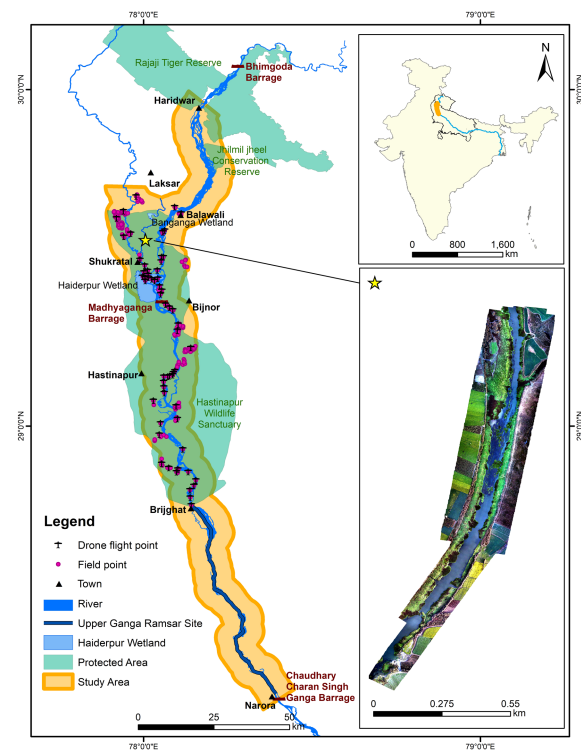


Fig. 1. Map depicts the location of the study area (a) within India and (b) extending from Haridwar to Narora, encompassing, showcasing major towns and barrages, key PAs, UAV survey points, and field points strategically selected for comprehensive data collection within the riparian zone including grasslands and wetlands. (c) Orthomosaic map of the selected area, surveyed using UAV, highlighting key features of the river, aquatic vegetation, grassland, and agricultural regions.

Once, widely covered by terai grasslands and riparian forests, the landscape has over the past centuries witnessed transformation into high-yielding agricultural lands. Unfortunately, the grassland habitat has been severely impacted by anthropogenic exploitation, which threatens the survival of species that depend on grasslands [12], [28], [29]. Flow modification, river bank agriculture, and growing urbanization imperil the open natural ecosystems in the floodplains. The river experiences low flow during nonmonsoonal periods because of the Bhimgoda, Madhya Ganga, and Narora barrages. The monsoon period from late July to August witnesses moderate flooding and events of animals, including deer getting washed away and drowning. The time from March to August is marked with cropping of Kharif crops, such as cucumber, bottle gourd, summer squash, bitter melon, pointed gourd, beans, pumpkin, tomato, and watermelon, on the river bed, islands, and along the river floodplains, encroaching the natural open spaces.

As the Ganga River is dynamic and susceptible to changes in the river's course, it is crucial to have an efficient monitoring system in place [59], [60]. Ecological monitoring of riparian habitat through field-based surveys is time-consuming and costly. In order to analyze and keep track of morphological changes, land use patterns, and vegetation dynamics in the riparian zones, it can be conducive to use remote sensing technology and earth observation data. Such monitoring initiatives can assist in determining the effects of river dynamics, human activity,

and climate change on riparian ecosystems and promote well-informed decision-making for their protection and sustainable management. However, many ground-level changes go unnoticed at the satellite level, and such primers or early indicators of change can be detected by leveraging drones, resulting in timely corrective measures. Procuring the training dataset for survey planning requires accurate and updated information from the field, which is sometimes very hard to achieve because of the dynamic nature of the river system [61]. Advancements in technologies such as Big Data analytics server-side processing have given rise to platforms such as Google Earth Engine (GEE). This has facilitated the rapid analysis and assessment of drone imagery and multitemporal high-resolution satellite data, enabling landscape monitoring. This study undertakes a nested approach to remote sensing, combining satellite data and UAV imagery to evaluate the condition of riparian habitats. GEE was utilized for normalized difference vegetation index (NDVI) based delineation of habitat clusters, which were then subsequently chosen for UAV-based assessment, resulting in the generation of very high resolution orthomosaic images and land cover maps for four different study sites. Using precise land cover classification, the level of habitat degradation can facilitate the implementation of effective conservation planning measures.

II. METHODOLOGY

A. Study Area

The study area (see Fig. 1) comprises a 240 km stretch of the Upper Ganga River from Haridwar in Uttarakhand to Narora in Uttar Pradesh, encompassing several ecologically significant regions: Rajaji Tiger Reserve (National Park and Elephant Reserve), Jhilmil Jheel Conservation Reserve (JJCR), Haiderpur Wetland, Hastinapur Wildlife Sanctuary (2073 km²), and the Upper Ganga Ramsar site. This region is also an important bird area (IBA) and part of the central Asian flyway. The major towns in this area are Balawala, Laksar, Haridwar, Bijnor, Brijghat, Narora situated within Dehradun, Haridwar, Bijnor, Mujaffarnagar, Amroha, Meerut, Hapur, and Bulandshahar districts.

The stretch from Haridwar has horizontal connectivity with forested islands covered with natural vegetation. Meanwhile, Bijnor to Narora consists of partly confined, braided channels with sidebars and midchannel bars [25]. Three barrages, Bhimgoda at Haridwar, Madhya Ganga at Bijnor, and Chaudhary Charan Singh Ganga Barrage at Narora, significantly modify the channels. This stretch of the river has undergone extensive industrialization, as seen by the abundance of sugarcane, paper pulp, and leather goods [30]. This area has a subtropical climate, with temperatures ranging from 44 °C in May to 7 °C in January, an average annual rainfall of 1300 mm recorded between 2000 and 2022, and peaks from June to September during the monsoon season. The 3664 km² within a 5 km buffer on both sides of the rivers Ganga and Solani was considered for vegetation analysis, mainly from Haridwar to Narora. The primary land use land cover comprises majorly agricultural cropland (67%), wetland (12%), forest (5.5%), plantation (4.5%), and scrub and grassland (2.5%), classes followed by settlement (4%), bare ground, and

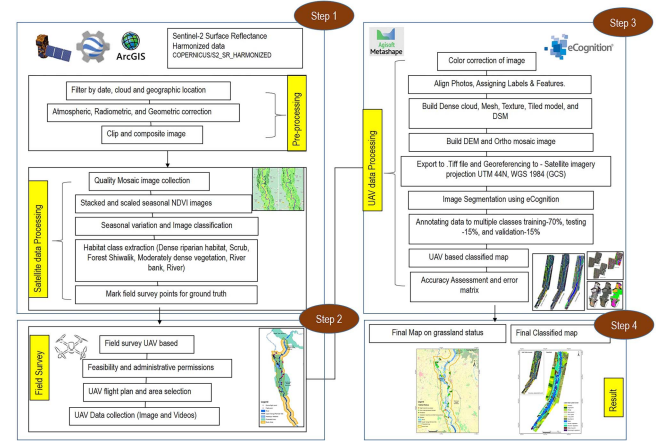


Fig. 2. Methodology flow diagram for using satellite imagery to identify survey points for riparian habitats. The drone survey plan, data acquisition, and processing pipeline play a pivotal role in prioritizing the riparian habitat.

sand bars (4%), respectively [31]. It lies in the Gangetic Plain (7A) biogeographic zone [32].

B. Method

Multispectral and multitemporal remote sensing data with local knowledge and simulation models have been successfully demonstrated as a valuable approach to identifying and monitoring grasslands and riparian habitats [33]. GEE is a robust cloud-based platform that allows users to access and analyze massive amounts of geospatial data. It supports various applications, including conservation planning and management [34], [35], [36]. GEE and remote sensing can be used in mapping and monitoring habitats, estimating animal populations, and mapping diverse landscapes and rivers [37], [38]. The high-resolution data obtained by UAV can result in precise classification results with processing based on multiresolution, multispectral object-based image analysis (OBIA) technique [39]. Forest officials, researchers, and conservationists use UAVs for monitoring and mapping of landscape structures [40], PAs [41], floodplain mapping [42], water quality assessments [43], and wildlife monitoring [44], [45]. A nested approach using remote sensing and drones are being used for assessing the habitat mapping and wetland status [21], [24], [46], [47], [48], agricultural applications [49], forestry [50], and feasibility of analyzing grasses [51].

In this study, we used satellite imagery as an assistive tool for drones to select riparian habitats for drone surveys. The procedure flow diagram of the proposed framework includes an outline of this multistep process, which is detailed in Fig. 2. The workflow of methodology in Section II includes Step 1, which derives the status of vegetation from satellite data and finalization of survey points; step 2, which involves preflight requisition, area selection, and data collection; step 3, which involves UAV data processing; and finally, step 4, which presents the results on an open platform.

1) *Satellite Imagery*: We used imagery with the GEE asset ID COPERNICUS/S2_SR_HARMONIZED for the years 2019 and 2022 on the GEE platform. This data refer to the

TABLE I

DETAILS OF THE FLIGHT PLAN FOR THE RIPARIAN HABITAT SURVEY, INCLUDING THE TYPE OF FLIGHT, LOCATION OF FLIGHT, PURPOSE, AND NO. OF FLIGHT, WERE TAKEN IN THE OBSERVATION

#	Date	Flight type	Location (Within study area)	Purpose	# Flights
1	09-02-2023	Scanning, Vertical	Inside Haiderpur Wetland, Ganga River	Mapping wetland and Grassland patches, scan status	12
2	10-02-2023	Scanning,	Daranagar ganj near Viduruti, Firozpur khader	To scan the river status, Grassland condition	10
3	11-02-2023	Scanning, Vertical	Nawalpur, Ranjeetpur	Sandbars, Agriculture, Grassland, mapping	11
4	12-02-2023	Scanning	Jalalpur kazi, Alampur Neela,	Agriculture, Grassland	7
5	13-02-2023	Scanning, Vertical	Bijnor Barrage, Haiderpur wetland east part	Mapping wetland and Grassland patches, scan status	5
6	19-02-2023	Scanning	Majlisipur, Teep	To scan the river status, Grassland condition	6
7	20-02-2023	Scanning, Vertical	Rampur Thakra	To scan the river status, Grassland condition, Mapping	10
8	21-02-2023	Scanning	Ujiyalli kalan	Grassland, converted agriculture, River status, Biodiversity	10
9	22-02-2023	Scanning	Makhdumpur, Sujatpur, Kjherikalan	Grassland, converted agriculture, River status, Biodiversity	16
10	23-02-2023	Scanning	Rasulpur, Sirjepur, Aidalpur	Grassland, Agriculture, mapping grassland, River status, Biodiversity	15
11	24-02-2023	Scanning	Bhogpur, Daranagar, Akbaarpur khadar	Grassland, converted agriculture, River status, Biodiversity	14
12	25-02-2023	Scanning	Tigri, Brijghat, Sarkari khadar	Grassland, converted agriculture, River status, Biodiversity	11
13	26-02-2023	Scanning	Shareefpur sumali, Meerapur	Grassland, converted agriculture, River status, Biodiversity	8
14	26-02-2023	Scanning	Dudhli, Sherpur	Grassland, converted agriculture, River status, Biodiversity	4
15	01-03-2023	Scanning	Jindawala, Almawala, Chamrawala, Sherpur	Grassland, converted agriculture, River status, Biodiversity	4
16	02-03-2023	Scanning	Jahanabad ahmatoli, Bela, Debkhadi	Grassland, converted agriculture, River status, Biodiversity	6
17	03-03-2023	Scanning	Chandpur, Bela, Debkhadi	Grassland, converted agriculture, River status, Biodiversity	4
18	04-03-2023	Scanning	Mahmudpur, Rafiul-nagar, Rawali, dungar	Grassland, converted agriculture, River status, Biodiversity	7
19	05-03-2023	Scanning	Abdipur, Razkallpur, Purkazi, Bahmanwala, Suheli, Faridpur, Damanpuri	Agriculture, Grassland	14
20	06-03-2023	Scanning, Vertical	Shukratal, Sukhtirth khader, Bihargarh	Agriculture, Grassland, mapping grassland, River status, Biodiversity	12
			77 locations		186

Harmonized Sentinel-2 multispectral instrument Level-2A, which has undergone a harmonization process to ensure uniform quality and radiometric accuracy. The different image collections for the four seasons of spring, rain, winter, and summer were created. The date range was properly filtered seasonwise, images were clipped to a designated boundary file, and a cloud cover threshold of up to 20% was maintained. To ensure proper analysis, the cloud masking “maskS2clouds” function was applied to identify and remove the cloud and cirrus pixels on the images. The NDVI was computed from the following equation for each seasonal image.

$$NDVI = (B8 - B4) / (B8 + B4) \dots (1)$$

where B8 stands for the near-infrared band and B4 for the red band, we applied the imageCollection.qualityMosaic() function to create a composite that enhances any band in the input of each seasonal NDVI image. In the seasonal NDVI image, we utilized the bands Blue (B2), Green (B3), Red (B4), NIR (B8), SWIR1 (B11), and SWIR2 (B12). The image in the collection with the highest pixel value for the designated band was identified for each pixel in the composite image. This allowed us to determine the greenest pixel in each composite image. Subsequently, each season’s greenest pixel composites were stacked into one image. The images were then scaled and stacked by multiplying by 100 and adding 100 to ensure a suitable data range. An unsigned 8-bit format was then applied to both year’s output images. The stacked and scaled NDVI images for both years were exported and added to the map for visualization, along with an RGB visualization. The regions, including dense vegetation, moderately

dense vegetation, scrub, Shiwalik forests, and cropland, were delineated utilizing ArcGIS software. The classified raster of NDVI was converted into polygons and cleaned to remove cropland, built-up, bare ground, sand, and other such classes. Only habitat clusters were retained. These also included plantations by the forest department, apart from riparian grasslands and scrub vegetation. We then filtered out approximately 1000 grassland patches with individual patch sizes greater than 1 ha. The major patches were shortlisted for field surveys based on size, connectivity, distance to water bodies, previously recorded species presence data, and feasibility of conducting drone surveys.

2) *UAV Imagery*: The drone and GPS (digital field mapping) based survey was conducted from February to April 2023, as detailed in Table I, using DJI Mavic 2 Enterprise Zoom, DJI Mavic Pro, and Garmin GPS for gathering georeferenced points, images, and video data. In compliance with regulations for flying drones, obtaining content permissions is crucial. We have diligently adhered to all relevant rules and obtained the necessary prerequisite permissions in Supplementary Information 5 (see Fig. S5-1, 2, 3, and 4). Among all the surveyed points, 203 grassland locations and 63 plantation locations were marked using 186 UAV flights (see Table I). A sample of UAV-based image and grassland status data taken from 77 different locations is also available in Supplementary Information 2 (see Table S2-2). The optical cameras on the UAVs were used to take photos and videos from various perspectives while flying at altitudes of up to 100 m. Four specific sites were selected for capturing vertical images with 75% side and frontal overlapping, 90 m altitude, and 4000*3000 px resolution to create orthomosaic

maps, namely Shekhpur Chamra and Shukratal in Muzaffarnagar, Ranjeetpur in Bijnor, and Sirjepur in Meerut district inside the study area. The orthomosaic maps were generated by using structure from motion based photogrammetric data pipeline technique using Agisoft Metashape professional - 64-bit version 1.8.5, ensuring detailed and accurate spatial information with 1.1 in per pixel DJI - FC220 sensor. This pipeline process involves photo alignment, camera optimization, dense cloud and mesh construction, the generation of tiled models and digital elevation models, and, finally, the preparation of the orthomosaic image for four different sites. A tabular summary of the UAV flight data is given in Supplementary Information 2 (see Table S2-1).

OBIA was conducted using eCognition developer 64 software. The primary objective was to process and analyze aerial imagery for land cover classification. The initial step in the analysis was multiresolution image segmentation, where the software segments the image into distinct objects or regions based on their visual characteristics. This process groups pixels with similar spectral and shape characteristics into meaningful objects that represent different land cover types. After image segmentation, we subjected the classified objects to a rule-based classification process. We used machine learning algorithms, spectral signatures, and contextual information to assign land cover labels to the segmented objects. This step aimed to identify and categorize different land cover types within the study area into different desired classes, such as aquatic vegetation, bare ground, small grass, tall grassland, mustard, riparian vegetation, *Saccharum*, submerged vegetation, sugarcane, water, water hyacinth, and wheat. We categorized vegetation at the genus level as follows: *Saccharum*, with its white fluorescence, and water hyacinth, showing a reddish-brown shade in the rotting phase. Species such as *Pistia*, *Azolla*, *Lemna*, and *Spirodella*, which had bright green color, were grouped as aquatic vegetation. *Valisneria*, *Stuckenia*, *Hydrilla*, *Potamogeton*, and *Ceratophyllum* were classified as submerged vegetation. *Enhydra*, *Polygonum*, *Ipomea*, *Ranunculus*, etc., were clustered as riparian vegetation due to their distinct spectral signature. We grouped the remaining tall grasses, such as *Imperata*, *Typha*, and *Phragmites*, as grassland. *Panicum*, *Cynodon*, *Commelina*, and *Cyperus* in open fields, banks, and pathways were categorized as short grasses.

Since most vegetation was spectrally similar, we further reclassified the preliminary classes. We defined rules based on size, shape, compactness, and distance for crop classes such as sugarcane, wheat, and mustard to restrict them to farmland. Subsequently, we applied similar procedure for riparian, aquatic, and submerged vegetation to limit them to areas within or near water bodies.

An accuracy assessment was conducted to ensure the reliability of the classification results. This involved comparing the classified land cover categories with ground truth data or reference datasets. A confusion matrix was used to calculate various accuracy metrics, such as overall accuracy, producer's accuracy, user's accuracy, and the Kappa coefficient. These metrics provided insights into the precision and reliability of the classification.

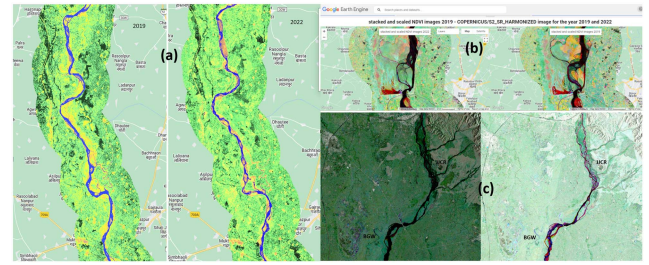


Fig. 3. (a) Annual NDVI composite for the period 2019 and 2022 in GEE visualization platform to compare changes in grassland, river course, and farmland. (b) and (c) Stacked and scaled seasonal NDVI composite for the period 2019 and 2022 of Haiderpur Wetland and seasonal SAR of 2021-2022 showing the riverscape between JJCR and BGW in the GEE visualization platform.

III. RESULTS

A. Satellite Imagery

The NDVI Composite image was visualized to delineate riparian vegetation within the study area. In Fig. 3(a), the dark green patches represent plantation that remains green even in the summer months, and the yellow regions represent scrubland. A comparison of the two images from 2019 and 2022 reveals the thinning of these patches. The NDVI composite image from Bijnor to Hastinapur, where the orange-brown color represents grasslands, shows that between the two images, some grasslands have disappeared due to changes in the river's course, while new grasslands have appeared in other areas. The temporal variations were distinct in Haiderpur Wetland, as seen in Fig. 3(b). The top frames display visually classified images.

The temporal NDVI composite image was visualized using color bands to highlight seasonal variations that differentiate riparian vegetation from agricultural areas within the study area. In the image, black regions represent water, bright red indicates aquatic vegetation; peach shows grassland patches; and yellow and light green represent agricultural fields. The seasonal SAR imagery stack in RGB shows the location of JJCR and Ban Ganga Wetland (BGW) along the Ganga River in Fig. 3(c). The perennial rivers, Solani and Banganga (from west to east), appear in black, while blue and red shades show seasonal variations. The seasonal wetlands to the west of BGW appear in blue. The BGW is also a tropical seasonal marsh that floods during monsoon from July to October and dries from May to June. The light green popped regions are dense vegetation.

B. UAV Imagery

We surveyed 203 grasslands and 61 plantations, other than 19 riverbanks, as detailed in Supplementary Information 1 (see Table S1-1). UAV imagery provided a thorough perspective of the terrain. We were able to spot disturbances or changes in land use patterns, vegetation cover, and potential signs of human activities. We categorized the status of the 284 field-surveyed points into 29 intact grassland patches, 87 good habitat patches, 25 patches recently converted into agriculture, and 60 patches either being converted into agriculture, remaining plantations, or water bodies. The intact grasslands need to be notified and

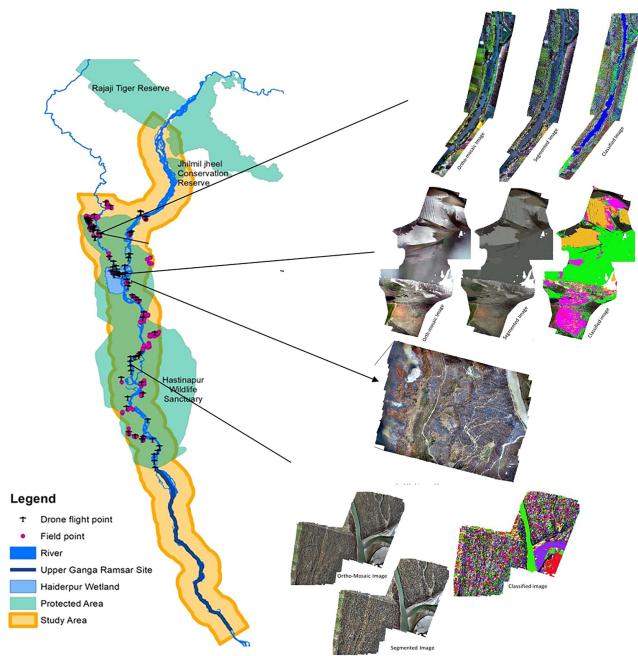


Fig. 4. Image representing the high-resolution orthophoto (~ 3 cm/px), segmentation result of site, and classified images of four strategic locations inside the study area. Pointed arrows on the map indicate the corresponding locations of UAV mapping.

earmarked to prevent land cover change, while the good habitat patches face the constant threat of conversion. We observed systematic clearance of grassland by local villagers in 60 of the patches, while 25 patches were entirely converted to farmland with cropping. We conducted drone flights at 77 of these sites.

Orthomosaic maps with segmented and classified images of four strategic locations, Shukratal, Ranjeetpur, Rampur Thakra, and Sirjepur, are shown in the figure. Among the four sites, Shukratal, Ranjeetpur, and Rampur Thakra displayed apparent signs of disturbance in the grassland biodiversity. These disturbances pose a significant threat to the natural grassland ecosystem and can result in habitat loss for various floral and faunal species that depend on these core areas. The fourth location, Sirjepur, shows intact grassland depicting a good habitat. The land use classification of four locations is shown in Fig. 4.

Many of these land use land cover change activities observed through drones needed to be clarified through satellite images. Although the latest satellite images cannot provide clear, conclusive evidence of the changes in land use land cover, the temporal imageries give an excellent indication to locate sites for fine-scale observations. This is for initial hints of activities that can cause change, which, if detected, can lead to appropriate corrective management decisions and, if undetected, can seriously damage the last remnant natural habitats and the biodiversity it fosters. However, once the land use change is completed, satellite images can be compared to pre- and postscenarios to quantify the affected area and estimate the loss. Thus, a complementary approach employing both of these remote sensing technologies effectively can strengthen conservation planning and PA management. As mentioned in Fig. 5 and Supplementary Information 1 (see Tables S1-1 and S1-2), seven patches have

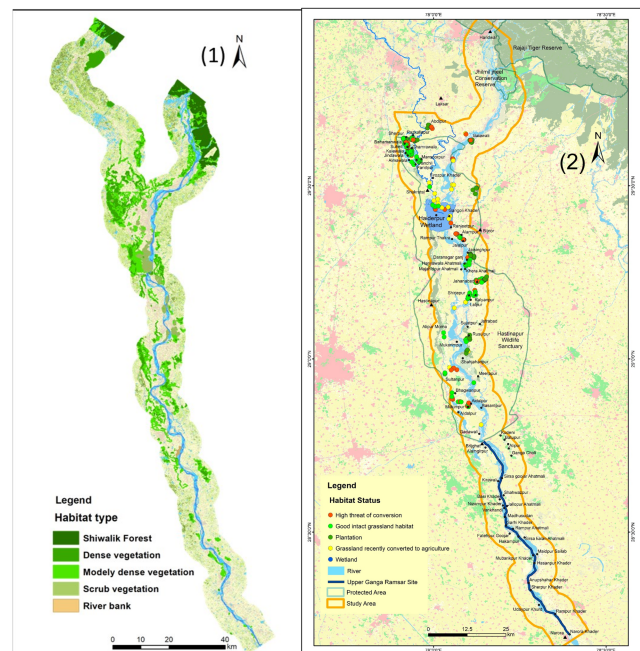


Fig. 5. Showcasing the result in two parts. First part is satellite-based habitat. Second part represents the current status of the study area, including areas with a high threat of conversion, intact grassland habitat in good condition, plantations, grassland recently under threat of conversion, and wetland points.

an area greater than 10 km^2 , and 54 patches have an area greater than 1 km^2 .

The largest identified patch covered an area of 23.56 km^2 , extending from Sherpur, Bahamanwala, Suheli, Chamrawala, Kalewala, Jindawala, Almawala, and Faridpur to Mansoorpur, along the boundaries of Uttarakhand and Uttar Pradesh. This giant patch comprises wetlands, grasslands, and a few plantations along the Solani River that support good biodiversity, including swamp deer, nilgai, spotted deer, and Sarus crane. We surveyed this largest habitat patch using 61 field points, of which 15 sites were surveyed through drone flights. Concerning the status of the habitat, 20 of these sites were found to be intact, 24 sites showed good biodiversity, and 17 sites showed signs of being threatened by conversion to agriculture. Most often, as a measure to dissuade encroachment of grasslands by local farmers, forest departments are forced to adopt plantation practices. Within a 1 km radius, we identified four small patches, of which we surveyed two locations using UAVs. Areas of 1.2 , 2.5 , 2.3 , and 1.5 km^2 are located near Panchli, Razkallapur above Purkazi-Laksar bridge, Jogawali, and near Kanhwali along Banganga river.

We surveyed the second patch using 13 field points and a drone flight and found it to have a suitable habitat but facing the threat of conversion. In contrast, the fourth patch, surveyed with three field points and a drone flight, had a suitable habitat and did not show any immediate threats. Riverscapes facilitate the movement of swamp deer (*Rucervus duvaucelii*); hence, these clusters along Solani and Banganga play a crucial role in sustaining them. The second largest patch cluster to its south is spread across 24.75 , 9.86 , and 4.9 km^2 . It is situated at the Solani, Banganga, and Ganga confluence in the Haiderpur wetland and Gangoli

Khader, Ranjeetpur, above the Madhya Ganga Barrage. Despite its importance as a RAMSAR site, 13 out of 8 sites surveyed through UAVs showed signs of conversion into agriculture and the presence of large herds of cattle, buffaloes explicitly, that deter shy animals such as deer.

Small grassland patches near Teep, Mirapur Khadar, Kunwarpur, and Raghunathpur along the Ganga showed threats of converting agriculture. Connecting these patches is essential for maintaining animal movement through the corridors. Below the Bijnor barrage, prominent patches near Rampur Thakra, Alampur, and Jalalpur covered an area of 2.9 km² and were surveyed with 23 field points. Of these ten points that indicated suitable habitat, three showed conversions to agriculture, and ten sites faced a threat of conversion. In addition, three river islands at Jaisinghpur, Daranagar Ahatmali, Hariyawala, Majahidpur Ahatmali, and Khera Ahatmali near Vidurkuti provide excellent grassland habitat with animal presence. These three river islands and bank habitats effectively covered an area of 3.5 km². We surveyed them using 23 field points. In Daranagar, two sites showed signs of conversion into grassland. We found 12 grassland patches to be intact and good habitats, while the remaining areas were plantations. Further south, Jahanabad had two patches, covering 1.58 and 0.88 km² surveyed with 25 points. We reported nine of these points as good, intact habitats, three sites as facing conversion threats, and the rest as plantations. Kalyanpur had a large patch of 4.8 km² with good habitat but with initial signs of clearance and conversion to agriculture. The adjacent cluster of river islands Sirjepur and Lalpur, which are 0.8 and 0.33 km² above Hastinapur Bridge, surveyed at seven points, also showed excellent habitat. Below the Hastinapur-Nandour Ganga bridge, a forest patch extends along the Madhya Ganga Canal. Toward Chandpur, most clusters consist of plantation patches, primarily located at Jaffarabad, Sujatpur, Rusulpur, Mukarimpur, Shahjahanpur, Mirapur, Bhagwantpur, Mukimpur, Aidampur, Basantpur, and Gadawali. However, they offer good habitat and support wildlife. Only some grassland patches are thriving between Bijnor and Narora, except for plantations maintained by the forest department or those on the river banks that change with the river's changing course. South of Brijghat to Narora, the major grassland scrubland patches are situated at Alamgirpur, Kudemi, Batupura, Bheema tekri, Alipur, Ganga choli, Kirawali, Sirsa Goojar, Shahwazpur, Basi Khader, Nizampur Khader, Jallopur Ahatmali, Vankhandi, Maduhasan Garhi Khadar, Fatehpur Gujar, Hakmpur Ahatmali, Rampur Ahatmali, Sisa Kalan Ahatmali, Mubarikpur, Hasanpur, Maidpur Sailab, Anupshahr Khadar, Sherpur Khadar, Udaypur khurd, Rampur Khadar, and Narora Khadar. The river in this stretch is dynamic, changing its course and shoreline with seasonal fluctuations. Map view in the GEE application is also available at <https://ee-ravindra1364.projects.earthengine.app/view/upperganganriverscape>.

Multiple survey points for riparian habitats representing the present condition of the study area are outlined in the drone survey plans shown in Supplementary Information 2 (see Fig. S2-1). High-resolution classified maps depicting the latest ground conditions are crucial for prioritizing the riparian habitat. A detailed orthomosaic image of the Shukratal site is depicted in Fig. 6, and a thematic map is produced by applying image

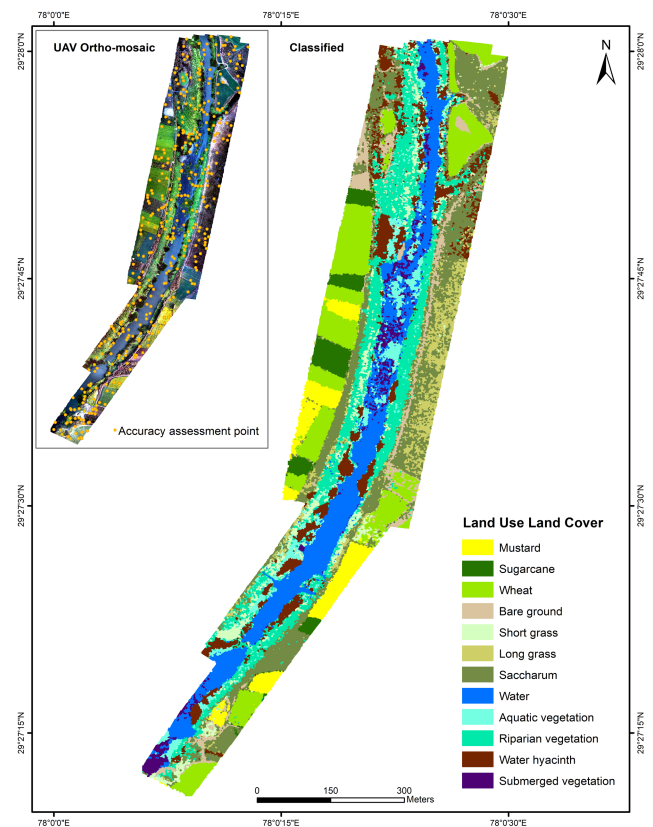


Fig. 6. High-resolution orthomosaic image of the site Shukratal representing a thematic map of the same areas generated after image segmentation and classification through the OBIA algorithm.

segmentation and classification through the OBIA algorithm. This high-resolution categorized view of the map enhances our understanding of the area's features, vegetation, and land use, as shown in Supplementary Information 3 (see Fig. S3-1 and 2).

The classification shows state-of-the-art performance with an overall accuracy of 98% and a kappa coefficient value of 0.97, as depicted in Table II. The results indicate 100% accuracy for small grass, tall grass, mustard, sugarcane, and wheat.

The lowest accuracy was 92% for riparian vegetation and 93% for submerged vegetation. Haiderpur RAMSAR site, located upper stream of the MGB on a Ganga River floodplain lies within the Asian Flyway. It is also known as home to diverse flora and fauna, including a wide array of threatened species. Within the Haiderpur wetland, nestled between the two channels of the River Ganga near Gangoli Khader and Ranjitpur, a UAV survey was conducted. This survey revealed extensive wheat cultivation in the area, as depicted in Fig. 7. We further checked through the GEE Sentinel-2 imagery for the months of February 2022 and February 2023 Fig. 7(a) and found an alarming increase in agriculture practices in the past few months. The UAV images in Fig. 7(b)–(f) depict clear evidence of systematic grassland clearance, indicating the shift in land use and raising concern about the preservation of this critical habitat. It is imperative to report such encroachment practices. Agricultural patches are clearly shown in the UAV images in Fig. 7(b), (c), and (f), surveyed in February–March 2023. A total of 11 flights were

TABLE II
STUDY PRESENTS CLASSIFICATION ACCURACIES AT THE SHUKRATAL SITE USING UNCREWED AERIAL SYSTEMS, DETAILING THEIR PERFORMANCE AND OUTCOMES

	Aquatic Vegetation	Barren	Short Grass	Tall Grass	Mustard	Riparian Vegetation	Saccharum	Submerged Vegetation	Sugarcane	Water	Water Hyacinth	Wheat	Total	User Accuracy	Kappa
Aquatic Vegetation	19	0	0	0	0	0	0	0	0	0	0	0	19	1.00	0.00
Barren	0	25	0	0	0	0	1	0	0	0	0	0	26	0.96	0.00
Short Grass	0	0	17	0	0	0	0	0	0	0	0	0	17	1.00	0.00
Tall Grass	0	0	0	20	0	1	0	0	0	0	0	0	21	0.95	0.00
Mustard	0	0	0	0	18	0	0	0	0	0	0	0	18	1.00	0.00
Riparian Vegetation	0	0	0	0	0	56	0	0	0	1	1	0	58	0.97	0.00
Saccharum	1	1	0	0	0	3	61	0	0	0	0	0	66	0.92	0.00
Submerged Vegetation	0	0	0	0	0	0	0	13	0	0	0	0	13	1.00	0.00
Sugarcane	0	0	0	0	0	0	0	0	13	0	0	0	13	1.00	0.00
Water	0	0	0	0	0	1	0	1	0	54	0	0	56	0.96	0.00
Water Hyacinth	0	0	0	0	0	0	0	0	0	0	30	0	30	1.00	0.00
Wheat	0	0	0	0	0	0	0	0	0	0	0	53	53	1.00	0.00
Total	20	26	17	20	18	61	62	14	13	55	31	53	390	0.00	0.00
Producer Accuracy	0.95	0.96	1.00	1.00	1.00	0.92	0.98	0.93	1.00	0.98	0.97	1.00	0.00	0.97	0.00
Kappa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.968

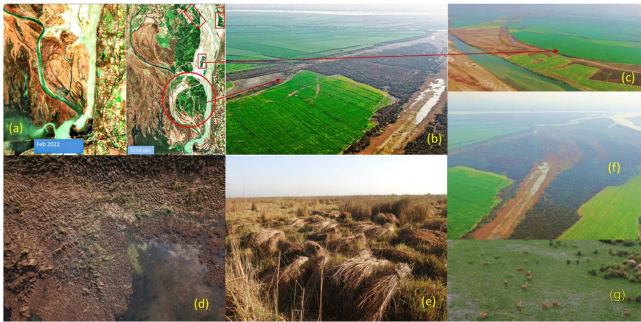


Fig. 7. This image plate showcases elements (a)–(g) captured within the Haiderpur wetland area. (a) Thematic map derived from sentinel satellite imagery over a two-year period. (b), (c), and (f) High-resolution UAV images depicting agricultural practices. (d) and (e) Aerial and close-up views of grass-cutting activities. (g) Presence of Swamp deer within the same habitat.

held in this location in scanning and vertical mode. In the same region, we recorded the presence of gharials, swamp deer Fig. 7(g), Nilgai, Indian grassbird, Black-necked stork, Painted stork, and various water birds, as illustrated in Supplementary Information 1 (see Fig. S1-1).

IV. DISCUSSION

Study design and technology integration can greatly improve the results of field surveys. Traditional methods of surveying landscape patterns are time, cost, and labor-intensive often impeded by spatial constraints of coverage and accessibility. Our technique achieves higher geographical resolution and greater detail by integrating freely available satellite data and consumer grade UAV imagery. This first phase of our study leverages freely available satellite data, particularly Sentinel-2, renowned for its

10 m resolution. Our primary tool for major land cover categorization marked the initial step in assessing riparian habitats through delineation. Through Sentinel-2 imagery, we identified key landscape features such as vegetation, wetlands, plantations, and grasslands, laying the foundation for our field research. However, higher resolution data became imperative for a more nuanced understanding of specific riparian habitats and detailed assessments of grassland status. This led us to designate strategic sites identified through satellite data as focal points for UAV data collection. Deploying consumer-grade drones, we conducted aerial surveys to obtain high-resolution information. This nested approach significantly enhanced our ability to detect intricate features such as aquatic vegetation, sugarcane patches, wheat fields, and various grassland areas—a critical second step in our study. This methodology proved essential in achieving comprehensive coverage of the extensive study area, circumventing the impracticality and time constraints associated with solely using consumer-grade drones for aerial surveys.

Data analysis is the next crucial phase. The UAV imagery was voluminous and difficult to ingest in software for analysis. This required careful preprocessing and transformation to align and integrate both datasets effectively. Handling the sheer volume of UAV data was particularly problematic, as software needed to work on managing and processing these large datasets efficiently. The non-GPU computer we used further compounded this issue, significantly slowing down the processing time for tasks such as generating orthomosaics and 3-D models.

Utilizing open-source platforms such as GEE provided access to multitemporal datasets and server-side processing of datasets saving processing time and enabling data access to pretested algorithms. Multiresolution segmentation and OBIA technique



Fig. 8. Illustrating the threats to grasslands. (a) Cattle wading through grasslands. (b) Grasslands being cut for agriculture. (c) Good habitat being used for wheat and seasonal vegetable production. (d) Sugarcane cultivation in a high-quality grassland habitat.

achieved very high accuracy in the classification of vegetation. Such a high level of accuracy for grasslands using remote sensing, particularly at such high resolution, could be achieved in this study. We identified and verified many species of aquatic vegetation such as *Typha elephantina*, Tall reed (*Phragmites karka*), and Munj (*Saccharum bengalense*), Bermuda grass (*Cynodon dactylon*), Kans grass (*Saccharum spontaneum*), Kunai grass (*Imperata cylindrical*) species, *Potamogeton crispus*, *Stuckenia*, *Vallisneria*, *Pistia*, *Polygonum*, *Ipomea*, *Panicum*, and *Vetiver*. Among these, we successfully classified the patches of *Pistia*, *Saccharum*, and *Phragmites* using our technique. During the survey, we came across the presence of several threatened species, such as swamp deer (*Rucervus duvaucelii*), gharial (*Gavialis gangeticus*), freshwater turtles, Gangetic dolphin (*Platanista gangetica*), and an array of threatened water birds, which accounts for a significant number of sightings. This signifies the existing quality of the riparian habitats in the study area. However, we observed an encroachment of grasslands for agriculture, sand mining, and uncontrolled grazing by livestock as significant threats to the landscape integrity in the region. These highlight the need for regular monitoring of the landscape in the face of growing threats and the value of the precious natural resources occurring in the area.

The five major threats prevalent throughout the study area were the clearing of grasslands, cattle grazing, riverbed agriculture, sand mining, and urbanization. Fig. 8(a), illustrating threats to grasslands, depicts cattle grazing in the grassland, and (b) highlights the conversion of grasslands into agricultural fields. In comparison, Fig. 8(c) and (d) shows a once-thriving habitat now used for cultivating wheat and seasonal vegetables.

Previous studies [12] through telemetry, GIS, and extensive fieldwork have generated quantitative information about prime grasslands in non-PAs and strongly advocated how such a model can generate more information and restore vulnerable grasslands that are primary swamp deer habitats. Another pioneering study

delineated arid grasslands as part of Open Natural Ecosystems in India to generate open datasets to support the conservation of these neglected ecosystems [52]. However, these studies were performed using Landsat data for their vast temporal coverage, with a ground resolution of 30 m or more. In this study Sentinel datasets with a ground resolution of 10 m was used for riparian habitat mapping and supplemented with data generated through UAV with a 3 cm ground resolution. The study focused on the present condition of riparian habitat, especially grassland and plantations within the study area, as the key focus of the research. Very few studies have been able to perform such fine-level classification of grasslands based on remote sensing data. Our study reaffirms the critical role of riparian grasslands in supporting a wide range of flora and fauna [29], [53], [54]. Grasslands provide habitat for a variety of bird species, small mammals, and insects with vital breeding, foraging, and shelter spaces [55]. Many of them have evolved to the specific biological circumstances of these environments. Riparian grasslands are essential for mitigation against floods by acting as buffers and fulfilling other ecosystem services, such as groundwater recharge and climate regulation, among others. This study reveals that grasslands are being converted into agricultural land even within the PAs or ecologically significant IBAs, and this rapid transformation poses a substantial threat to biodiversity as it disrupts the crucial biodiversity of Swamp deer and other species [28], [54]. The Banganga wetland, a wetland of international significance that served as vital connectivity to the seasonal migration of swamp deer from Jhilmil Jheel, needs attention. Many small wetlands and natural depressions have been reclaimed and have been converted into farmland, disrupting connectivity for swamp deer. Roads and railway lines also fragmented the landscape. Hence, in such a scenario, the management practices should also consider the permeability of the landscape for wildlife and undertake steps toward maintaining the habitat connectivities. Grasslands are generally overlooked ecosystems [56]. Maintaining intact grasslands can ensure the survival of multiple riparian species, enhance riparian habitat quality, and boost vibrant wildlife corridors [62], [63]. Cooperation between governmental organizations, conservation groups, and local people is necessary to preserve these vital grassland habitats. Protection of riverscapes and their zonation in development plans is essential to arrest unplanned development and land use change to protect grasslands that act as refuge for aquatic and semiaquatic animals of Ganga River.

Satellite data are cost-effective and offer wide coverage and context, whereas UAVs allow us to capture fine-scale details and variations within riparian habitats. This combination provides a more complete picture of habitat structure and dynamics. This approach is scalable and suitable at several spatial scales from local to regional. The scalability is critical for addressing habitat dynamics and differences in management requirements across varied riparian landscapes. Such templates can be replicated for other rivers or areas of interest along the rivers, such as PAs, IBAs, Ramsar sites, and wetlands of international importance in other major rivers. Technology can play a key role in facilitating data backed decision making. Many interactive, simple, user friendly, open-source online applications such as Earth Engine and Sentinel Playground can offer visualization tools that can be

availed by decision makers and administrators to look up their area of interest [52].

V. CONCLUSION

This study's implications go beyond the study site, involving high-precision techniques with the potential to aid riparian habitat assessment with global conservation benefits. This UAV-satellite-based nested approach enables rapid habitat assessment for effective biodiversity conservation monitoring. Our final product offers policy-makers and administrators with a web-based, science-backed technological platform that can aid data-driven decision making. UAV-based ecological studies are still in the nascent phase in India. Similar aquatic terrestrial zone-specific UAV-based studies for ecological monitoring are in the developing phase, so this methodology and data assessment can provide baseline information for further drone-based studies for grassland and riparian habitat monitoring which is essential for biodiversity conservation.

India harbors 10% of the world's global freshwater biodiversity, while sharing only 4% of the global fresh water reserve. For such a country with the world's largest population, conservation is a great challenge. India is committed to the Ramsar Conventions and has not only declared Ganga as the National River (in 2008), launched a "Mission for Clean Ganga" (2014) but also added 38 new sites since 2020 to its renewed list of 75 Ramsar sites. It has also recognized the endemic Gangetic dolphin as its National Aquatic animal as a flagship toward aquatic species conservation. Scientific and technological support with hot spot identification, threat detection, and biodiversity heat maps can serve practical purposes regarding governance and assist judicious conservation action. Conservation of these riparian habitats can help achieve various targets and contribute toward India's efforts to meet the Global Biodiversity Framework 2022 goal to restore ecosystems. It also prevents species extinction and supports Sustainable Development Goals – 6 (Clean water), 13 (Climate action), 14 (Life underwater), and 15 (Life on Earth). Benefits of protecting these sites include floodplain protection, replenishment of aquifers, protection of the Asian flyway, and reduced siltation and erosion that can play a crucial role in the river morphology. It can also ensure maintaining eco-hydrology and river depth that can critically affect dolphin population isolated between Bijnor and Narora barrage while also acting as a safe aquatic harbor and source for a population of gharial and turtles that are concentrated in this stretch of the river as opposed to the entire Ganga River. The Ganga Habitat block also supports the endemic Northern swamp deer populations and the grasslands need to be protected to conserve these obligatory grassland species [28].

A pan India assessment of faunal species across Ramsar wetlands enlisted 26, 72, and 42 species, respectively, as Critically Endangered, Endangered, and Vulnerable [57]. The Species Threat Abatement and Restoration STAR score for India, developed by Chaudhary et al. [58], comprehensively identified 97 individual threats affecting species, of which the primary threat of crop production (contributing 44% of the total), followed by biological resource use such as hunting and logging (23%), and residential and commercial development (11%) constituted

three quarter of the total threats. Therefore, species conservation planning requires strategies to reduce and resist these threats. However, while protecting wild habitats, it is important to also respect the rights of local communities to these resources. Instead of denying permissions to locals visiting inside, we can prevent land from being converted into agriculture by promoting permaculture and agroforestry, encouraging sustainable uses of grasses, improving skills, educating people about species importance, raising awareness of threats, and banning harmful chemicals in riparian zones. Protection of these precious resources is a combined responsibility and needs timely, targeted, and united action. We recommend regular monitoring, change tracking, and early threat detection for riparian hotspots. We also recommend open online platforms such as GEE that can be utilized to view temporal data for comparative assessment. We attest and advocate the utility of UAVs for effective early threat detection, surveillance, and fine-scale habitat mapping, even of difficult habitats such as grasslands and floodplains. Apart from this zonation of floodplains and clear demarcation of "no development zones," strict implementation of "no chemical fertilizers or pesticides" in floodplains, supervised development in riparian zones, controlled mining, etc., could be some measures to preserve the intactness of riparian habitats.

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