

EXPLORED AND DEMONSTRATED POTENTIAL APPLICATIONS OF MULTI-PARAMETRIC SYNTHETIC APERTURE RADAR IN WETLAND STUDIES IN CONTEXT OF KEOLADEO NATIONAL PARK, BHARATPUR, INDIA

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Wetland ecosystems have received little recognition on the vital role that they play for human well being. As a result of this, there is an alarming loss of wetlands. It is required to arrest the losses and to achieve optimal resource use with balanced priorities of biodiversity conservation. This calls for meaningful and timely information and data on wetland habitats, its fauna, flora and socioeconomic variables of relevance. Traditionally, the source of the spatial information that captures dynamics of a wetland ecosystem has been that of optical remote sensing data. Although optical remote sensing data is found to be very useful for wetland monitoring, cloud cover restricts the availability of satellite data during rainy season, which is main source of water for most of the inland wetlands. Moreover, delineation of several classes of importance for wetland ecosystem is also not clearly differentiable on optical remote sensing data. Synthetic Aperture Radar (SAR) can play an important role to achieve the above goals. Due to their unique response to open water and water with varying vegetation coupled with their all weather capability, SAR sensors are the best choice for monitoring of a wetland ecosystem. In this article, authors address the dynamics of wetland habitat using satellite data from optical (IRS-L-III) and multi-parametric SAR sensors (ERS-1/2, Multi-incidence angle RADARSAT-1, Multi-incidence & Multi-polarized ENVISAT-1 ASAR, multi-parametric DLR-ESAR) over Keoladeo National Park, Bharatpur, India acquired between 1996 and 2004. Results of the study clearly indicate that use of SAR data can improve quality of information on various components of a wetland ecosystem, which is of great significance in wetland conservation and monitoring.

1.0 INTRODUCTION

Wetlands are defined as lands transitional between terrestrial and aquatic eco-systems where water table is usually at or near the surface or the land is covered by shallow water. Due to their intermediate position they are particularly sensitive to changes in their normal patterns of water storage and management (Middleman, 1990; Shukla and Dubey, 1996). Wetlands are dynamic systems and therefore they exhibit rapid temporal fluxes in the structure and function of the ecosystem. This is in contrast to the terrestrial ecosystems, where the changes in space and time are relatively less spectacular and apparent. Wetlands play an important role in ground water recharge and also provide unique habitats for wide range of flora and fauna. Wetlands are present on every continent except Antarctica and in every climate from tropics to tundra. It has been estimated that nearly 6% of the total land surface of the world is under wetland (Maltby and Turner, 1983).

Although wetlands have significant biodiversity resources, the recognition of biodiversity conservation values of the wetlands has been neglected for a long time. As a result of this, there is an alarming loss of wetlands. The alarming loss of wetlands all over the globe had initiated an inter-governmental treaty which provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. This treaty was signed in Ramsar, Iran, in 1971 and is known as 'Ramsar Convention'. There are presently 158 Contracting Parties to the Convention, with 1721 wetland sites, totalling 159 million hectares, designated for inclusion in the Ramsar List of Wetlands of International Importance. (Ramsar website: <http://www.ramsar.org>). In order to monitor wetlands, on local, regional and national levels, there is an urgent need to develop user friendly and cost effective tools. Remote sensing can play an important role for assessment, monitoring and management of wetland ecosystem. Lot of work has already been done in the field of wetland studies using data from conventional remote sensing sensors operating in optical and infrared region of the

electromagnetic spectrum (Carbonell, 2002; Mahlke, 1996; Reynolds, et al., 2006; Shanmugam, et al., 2006). However, for studies of wetland, optical remote sensing data exhibit a few limitations. In contrast to radar remote sensing, the major limitation with optical data is uncertainty of getting cloud free data during monsoon (rainy) season. The analysis during monsoon season is of prime importance as it is the main source of water that controls the ecosystem of a wetland. Moreover, sensitivity of optical data for textural variation of vegetation (both terrestrial and aquatic) is also limited as compared with Radar data operating in the microwave region of the electromagnetic spectrum, which is highly sensitive for the texture of the imaging terrain. Capability of microwave signals transmitted from the Synthetic Aperture Radar (SAR) sensor to penetrate vegetation cover and to sense the moisture content of the earth materials, allows microwaves to monitor the wetland ecosystem more accurately as compared to optical remote sensing tools.

However, use of Radar data for wetland studies has attracted less attention as compared to use of Radar in other applications like agriculture, forestry, soil moisture etc. Although the use of radar in wetland inventory, assessment and monitoring has not get enough momentum, the potential of radar in wetland has started receiving recognition from various agencies and organizations worldwide. Recently, Ramsar Convention secretariat in its technical report has highlighted the potential of Radar data in the assessment, monitoring and management of wetlands (Lowry, 2006). Davidson and Finlayson, (2007) also emphasized the role of longer wavelengths (L-band) in wetland inventory. Rosenqvist, et al., (2007) has demonstrated that Radar remote sensing can help in implementation of the Ramsar wetland convention. Hence, there is a huge potential to explore the use of Radar remote sensing in wetland inventory (Chapman, et al., 2001; Hess & Melack, 1994; Forsberg, et al., 2000; Patel & Srivastava, 2004). In this article, an attempt has been made to explore and demonstrate the potential applications of Radar data from variety of sensors over a pilot study area, which can form a basis to promote use of Radar remote sensing applications in wetland inventory particularly in south Asian countries. For this purpose, world famous Keoladeo National Park, Bharatpur, India has been selected as study area. A number of Synthetic Aperture Radar (SAR) data sets acquired from different satellites operating at various combinations of SAR sensor parameters from the year 1996 to 2004 have been studied. This article brings out the silent findings of the work done over Keoladeo National Park along with the feasibility of use of Radar data acquired at different sensor parameters for wetland inventory that can be used as an input for the assessment, monitoring and management of a wetland ecosystem.

2.0 IMPACT OF SENSOR AND TARGET PARAMETERS ON INTERACTION OF SAR BACKSCATTER WITH VARIOUS COMPONENTS OF A WETLAND ECOSYSTEM

SAR backscatter depends upon chosen sensor parameters {wavelength (λ), incidence angle (θ) and transmit/receive polarization} as well as target properties. A careful selection of sensor parameters can significantly enhance sensitivity of SAR for a specified application. Penetration capability of microwave signal from Synthetic Aperture Radar (SAR) is very useful for wetland applications. Penetration depth of Radar signal depends upon the wavelength along with the dielectric properties (moisture content) of the target and is given by following equation.

$$\delta = \frac{\lambda \sqrt{\epsilon'}}{2\pi\epsilon''}$$

[Where: δ = Penetration Depth; λ = Radar Wavelength; ϵ' = Real part of dielectric constant; ϵ'' = Imaginary part of dielectric constant]

Thus longer wavelengths can penetrate deeper through vegetation cover and soil as compared to shorter wavelengths. This penetration capability is very useful to collect the information underneath the vegetation cover or below the soil surface (Srivastava, 2007a). In the context of a wetland ecosystem, this quality is useful to know whether there is standing water below the aquatic vegetation or the soil below vegetation is wet, moist or dry. The capability of SAR to penetrate is also useful to collect information about the under story vegetation and flooding under tree cover (Ormsby, et al., 1985). Potential of multi-frequency SAR data in wetland studies due to the difference in penetration depths of different bands has been demonstrated by Yamagata & Yasuoka, (1993). They demonstrated that due to difference in wavelengths (or in other words penetration depths) of JERS-1 SAR and ERS-1 SAR, the bog and the fen vegetation in the wetland can be segregated using JERS-1 SAR image, whereas the swamp forest can be delineated from the fen vegetation using ERS-1 image.

Incidence angle and polarization are other important sensor parameters that can significantly affect SAR backscatter from same target. In case of a smooth bare surface, reflection of SAR signal is described by the Fresnel reflectivity Γ . The Fresnel reflectivity characterizes reflection of a transmitted wave at the interface between the air and the soil surface. The Fresnel coefficient Γ is given by,

$$\Gamma_h(\theta) = \frac{\mu \cos \theta - \sqrt{\mu \epsilon - \sin^2 \theta}}{\mu \cos \theta + \sqrt{\mu \epsilon - \sin^2 \theta}} \quad \Gamma_v(\theta) = \frac{\epsilon \cos \theta - \sqrt{\mu \epsilon - \sin^2 \theta}}{\epsilon \cos \theta + \sqrt{\mu \epsilon - \sin^2 \theta}}$$

{Where, Γ_h and Γ_v are the horizontal and vertical polarizations of the EM wave}

The response of horizontal polarization increases with increasing the local incidence angle. The vertical polarization response decreases to zero at a certain angle, the so called Brewster Angle (the angle under which the transmitted wave is completely absorbed by the dielectric medium) and then increases suddenly with further increase of the local incidence angle.

Like wavelength, incidence angle can also be selected to enhance the sensitivity of SAR for a particular application. Srivastava, et al., (2002a) observed that high incidence angle SAR data is more sensitive for vegetation cover. It is due to the fact that higher incidence angle increases the slant height of vegetation and forces the signal to travel longer distances through the vegetation cover as compared to lower incidence angles. In the perspective of a wetland ecosystem, selection of lower or higher incidence angle SAR data can increase or

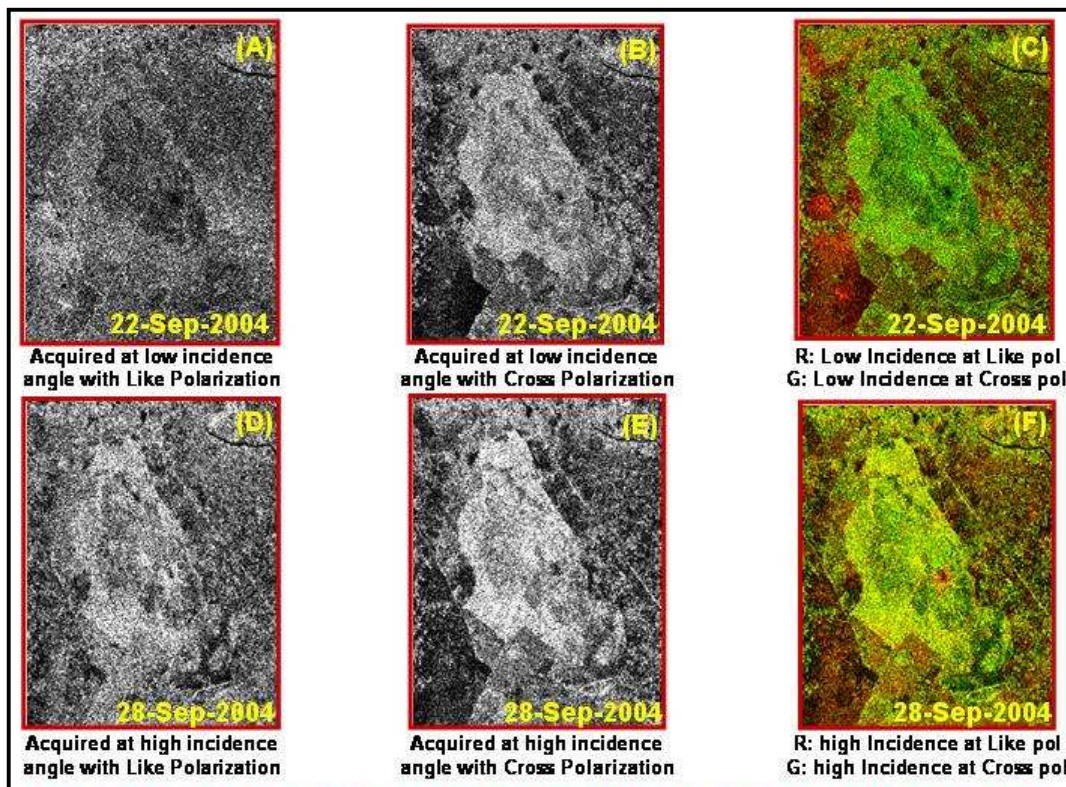


Figure 1: Multi-incidence angle (IS-1 & IS-5) and Multi-polarized (VV & VH) ENVISAT-1 ASAR sub-images over Keoladeo National Park showing the impact of low and high incidence angles acquired at like and cross-polarization on SAR image.

decrease the capability of SAR signal to collect the information below the aquatic vegetation. **Figure-1** shows the dramatic effect of incidence angle on SAR image and also its usefulness for wetland studies. **Figure-1** clearly demonstrate that by selecting high incidence angle SAR data (**Figure-1 D**), more information can be collected about the aquatic vegetation and grasses, whereas selection of low incidence angle SAR data (**Figure-1 A**) reduces the slant height of the aquatic vegetation and grasses, resulting in higher sensitivity towards the moisture

status and / or standing water underneath the aquatic vegetation and grasses. Hence, if a user is interested to map aquatic vegetation, higher incidence angles are preferred whereas to map the extent of water below the aquatic vegetation, lower incidence angle SAR data acquired at longer wavelengths is preferred. Along with wavelength and incidence angle, proper selection of transmit and receive polarization is also very crucial and one need to be careful in selecting the appropriate combination according to ones objective. For example, VV polarization interact more with vertically oriented aquatic vegetation (Srivastava, et al., 2002b) whereas HH polarization is more sensitive for horizontally structured vegetation like *Prosopis juliflora* (Patel, et al., 2006a). Cross-polarized SAR data is also very useful for wetland studies as it is highly sensitive to not only the aquatic vegetation and grasses but also to forest cover and other upland vegetation (**Figure-1 B&E**). Comparison of **Figure-1(B)** and **Figure-1(E)** indicate that irrespective of incidence angle, cross-polarized SAR data is always more sensitive to aquatic vegetation, grasses and forest cover.

As mentioned, apart from sensor parameters, the target properties also significantly affect the SAR backscatter. These are moisture content of vegetation or soil, surface roughness, structure of the vegetation, textural properties of the target, orientation of the target etc. The key factor due to which Radar data is sensitive to soil moisture is the large difference between the dielectric constant of dry soil (3 to 4) and water (about 80) at microwave frequencies (Ulaby, et al., 1990). Although, SAR backscatter is highly sensitive to soil moisture, there are several issues in soil moisture estimation using SAR data, as along with soil moisture, SAR backscatter is also sensitive to other target properties like vegetation cover, surface roughness and soil texture/soil type. However, there are ways to incorporate the effects of vegetation cover, surface roughness and soil texture in soil moisture estimation using multi-parametric SAR data. One such methodology has been proposed by Srivastava, et al., (2006a), for large area soil moisture estimation using SAR data. From the view point of a wetland ecosystem, sensitivity of SAR backscatter towards moisture content of soil can be used to locate localities of high soil moisture zones whereas sensitivity of SAR backscatter towards vegetation structure and vegetation moisture can be used to discriminate various species of aquatic vegetation. Sensitivity of SAR data towards vegetation parameters has been explored by many researchers. For example, Patel, et. al., (2006b) demonstrated that by proper selection of sensor parameters, plant parameters can be retrieved from the SAR backscatter.

3.0 STUDY AREA AND DATA SET

The study area is located in Keoladeo National Park, Bharatpur, India. This is a world Heritage and Ramsar site. It is an important staging ground for waterfowl and also to the rare and dwindling Siberian Cranes. The study area

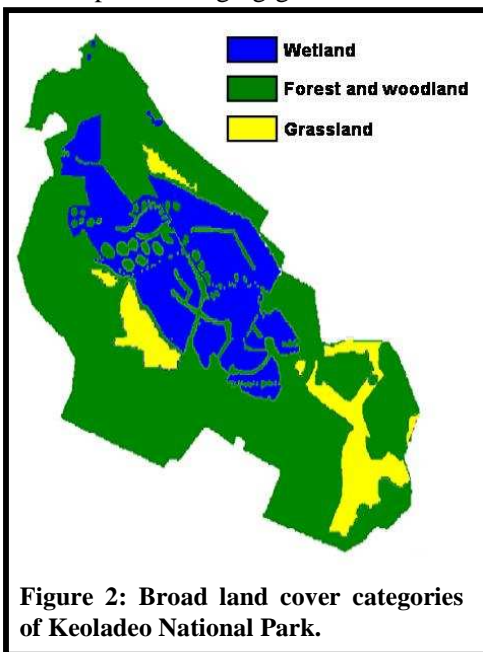


Figure 2: Broad land cover categories of Keoladeo National Park.

has a tropical monsoon-climate. A mixture of *Prosopis juliflora*, *Acacia nilotica* and *Salvadora* species dominate the vegetation. The aquatic vegetation has *Ipomoea*, *Paspalum distichum* and weeds such as *Eichhornia*. In some parts of the sanctuary (southeastern parts) extensive occurrence of *Vetivera zizanoides* is noted. A detailed list is available in Perennou (1987). Resident birds use the sanctuary for breeding purposes. Many species use open water habitat and localities of free floating and emergent aquatic vegetation. Areas totally dominated by *Paspalum*, *Eichhornia* are not preferred by many species except for purple moorhen, Jacanas and few others. From a biodiversity perspective, this park is one of the remarkable parks in the world harboring about 379 angiosperms, over 350 bird species and 27 mammals. Few camera-captured field photographs showing different wetland habitats and various residents of Keoladeo National Park are included at the end of this article in the form of five plates entitled “Keoladeo National Park in different Moods & Colours”. **Figure-2** shows the broad land cover categories found in Keoladeo National Park. For the study reported in this article, several data sets of multi-incidence angle, multi-polarized, multi-frequency, temporal, InSAR and fine resolution Synthetic Aperture Radar (SAR)

data from ERS-1/2 SAR tandem pair, RADARSAT-1 SAR, ERS-2 SAR, ENVISAT-1 ASAR and DLR E-SAR acquired over Keoladeo National Park during 1996 to 2004 have been analyzed. Details of Radar data used in the

study are given in **Table-1**. Spatial resolutions of the acquired SAR data sets range from 4 meter to 35 meters. In order to highlight the potential of SAR data and also for the comparison purpose, several optical and IR remote sensing data sets from IRS (Indian Remote Sensing Satellite) LISS-III (Linear Imaging Self Scanning-III) have also been acquired over Keoladeo National Park. Spectral bands of IRS LISS-III are Green (0.52-0.59 μ m), Red (0.62-0.68 μ m), Infra red (0.77-0.86 μ m) and Short wave Infrared (1.55-1.70 μ m) with the spatial resolution of 23.5 m.

S. No	Satellite	Platform	Beam Mode	Band / Sensor	Orbit/ Path:Row	Polarization	Central Incidence angle (θ)	Nominal Resolution	Date of Pass
01.	ERS-1	Space borne	Tandem	C / SAR	24556	VV	23°	30 m	26-Mar-1996
02.	ERS-2				04883				27-Mar-1996
03.	ERS-1	Space borne	Tandem	C / SAR	24828	VV	23°	30 m	14-Apr-1996
04.	ERS-2				05155				15-Apr-1996
05.	ERS-1	Space borne	Tandem	C / SAR	25057	VV	23°	30 m	30-Apr-1996
06.	ERS-2				05384				01-May-1996
07.	RADARSAT-1	Space borne	Standard-1	C / SAR	11919	HH	23°	25 m	15-Feb-1998
08.	ERS-2	Space borne		C / SAR	742/192	VV	23°	30 m	08-Feb-1998
09.	RADARSAT-1	Space borne	Extended Low-1	C / SAR	17507	HH	16°	35 m	13-Mar-1999
10.	RADARSAT-1	Space borne	Standard-4	C / SAR	17550	HH	36°	25 m	16-Mar-1999
11.	RADARSAT-1	Space borne	Extended Low-1	C / SAR	22759	HH	16°	35 m	15-Mar-2000
12.	RADARSAT-1	Space borne	Standard-6	C / SAR	23159	HH	43°	25 m	12-Apr-2000
13.	RADARSAT-1	Space borne	Fine 2 N	C / SAR	30262	HH	40°	8 m	22-Aug-2001
14.	RADARSAT-1	Space borne	Fine 2 N	C / SAR	30948	HH	40°	8 m	10-Oct-2001
15.	RADARSAT-1	Space borne	Fine 2 N	C / SAR	31634	HH	40°	8 m	26-Nov-2001
16.	RADARSAT-1	Space borne	Fine 2 N	C / SAR	32320	HH	40°	8 m	13-Jan-2002
17.	ENVISAT-1	Space borne	IS-1	C / SAR	13407	VV/VH	18°	30 m	22-Sep-2004
18.	ENVISAT-1	Space borne	IS-5	C / SAR	13493	VV/VH	38°	30 m	28-Sep-2004
19.	DLR E-SAR	Air borne	dual-pol	C / SAR	-	VV/ VH, HH/HV	28°-65°	4 m	19-Sep-2004
20.	DLR E-SAR Repeat Pass	Air borne	Polarimetric	L / SAR	-	VV,HH,HV,VH	28°-65°	4 m	19-Sep-2004
21.	DLR E-SAR Repeat Pass	Airborne	Polarimetric	P / SAR	-	VV,HH,HV,VH	28°-65°	4 m	19-Sep-2004

Table-1: Details of Multi-parametric Synthetic Aperture Radar (SAR) data used in the analysis

4.0 METHODOLOGY

4.1 Ground truth data collection

Field information regarding various wetland habitats of Keoladeo National Park like open water habitat, aquatic vegetation, grassland, vegetation type and its orientation were recorded. Soil samples were collected at various depths to know the surface soil moisture along with soil moisture status in soil profile at several strategic locations inside the park. Vector layers of all the major categories along with the locations have been recorded with the help of a Global Positioning System (GPS) based mobile mapping unit. **Figure-3** and **Figure-4** show traced vector boundaries of various blocks and road network of Keoladeo National Park with the help of GPS based mobile mapping unit. Area and perimeter of various blocks of Keoladeo National Park derived from GPS based mobile mapping unit is given in **Table-2**.

4.2 Image Pre-processing

First of all, all the SAR images were radiometrically calibrated followed by speckle suppression using enhanced Lee filtering algorithm (Lee, 1986) with a 3x3 window. Then from the large number of IRS LISS-III images, one image has been geo-referenced using the ground control points. After wards all the optical and SAR images were co-registered using nearest neighbourhood method of resampling (Duggin and Robinore, 1990). The road / rail, canal / drainage networks and ground truth locations were digitised and transferred on the image. After the

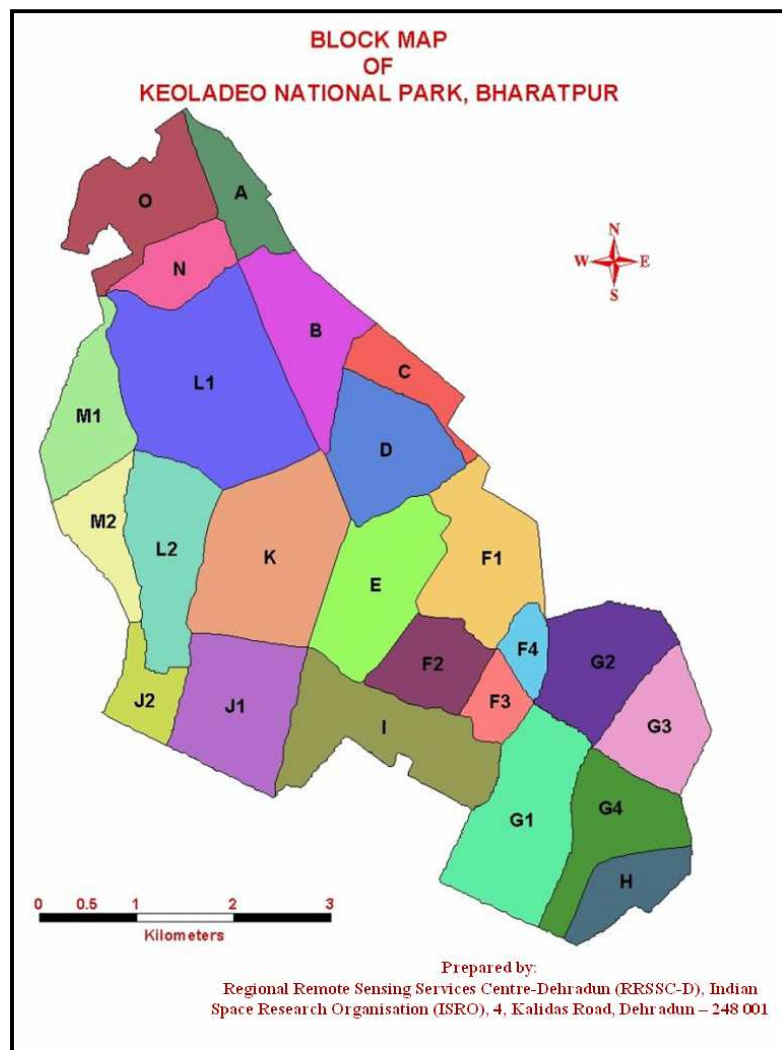


Figure-3: Vector boundaries of various blocks of Keoladeo National Park traced with GPS based Mobile Mapping Unit

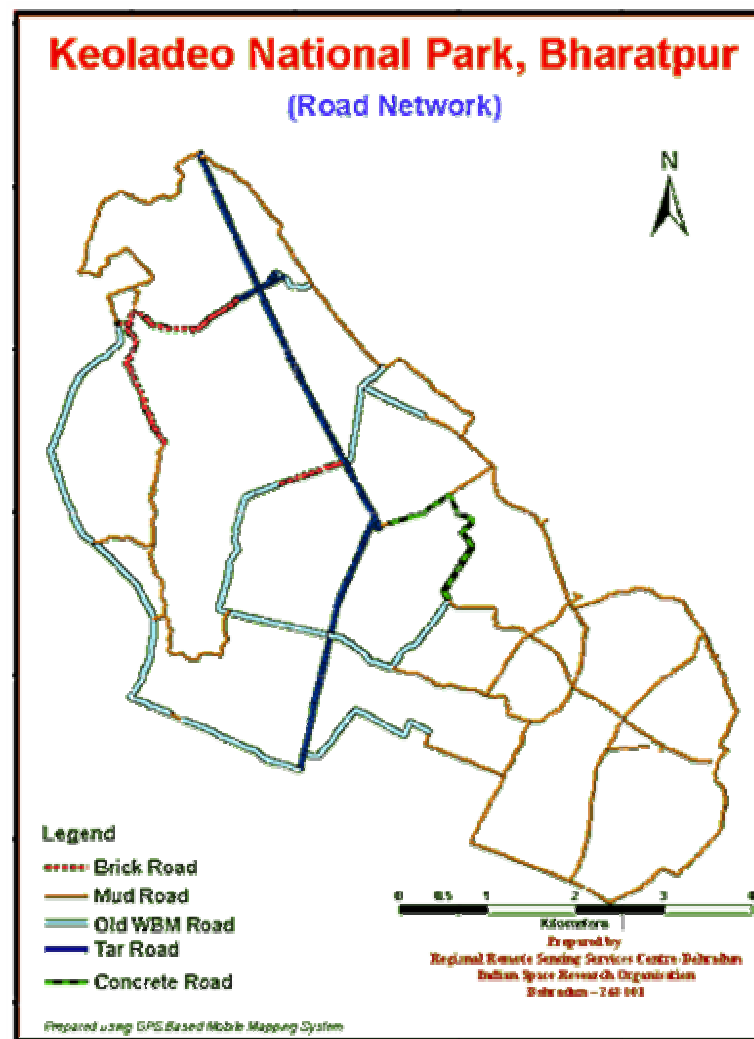


Figure-4: Park boundary and road network of Keoladeo National Park traced with GPS based mobile mapping unit.

availability of GPS based mobile mapping unit, the vector layers traced during the field work have directly been transferred on to the geo-referenced multi-sensor satellite data sets.

AREA AND PERIMETER OF ALL THE BLOCKS IN KEOLADEO NATIONAL PARK DERIVED FROM SATELLITE DATA AND GPS								
BLOCK	IN METERS		BLOCK	IN KILOMETERS		BLOCK	IN HACTARES	
	AREA	PERIMETER		AREA	PERIMETER		AREA	BLOCK
A	679294.0	4427.039	A	0.6792940	4.427039	A	67.92940	A
B	1316310.0	5515.422	B	1.3163100	5.515422	B	131.63100	B
C	556761.6	4433.762	C	0.5567616	4.433762	C	55.67616	C
D	1388404.0	4812.834	D	1.3884040	4.812834	D	138.84040	D
E	1559937.0	5392.541	E	1.5599370	5.392541	E	155.99370	E
F1	1510726.0	6101.373	F1	1.5107260	6.101373	F1	151.07260	F1
F2	830380.9	3764.960	F2	0.8303809	3.764960	F2	83.03809	F2
F3	398948.8	2650.630	F3	0.3989488	2.650630	F3	39.89488	F3
F4	328346.8	2496.845	F4	0.3283468	2.496845	F4	32.83468	F4
G1	1908772.0	6485.704	G1	1.9087720	6.485704	G1	190.87720	G1
G2	1285716.0	4991.667	G2	1.2857160	4.991667	G2	128.57160	G2
G3	1010725.0	4234.878	G3	1.0107250	4.234878	G3	101.07250	G3
G4	1197627.0	5840.647	G4	1.1976270	5.840647	G4	119.76270	G4
H	659753.7	3838.514	H	0.6597537	3.838514	H	65.97537	H
I	1751830.0	7892.397	I	1.7518300	7.892397	I	175.18300	I
J1	1596493.0	5347.342	J1	1.5964930	5.347342	J1	159.64930	J1
J2	533413.5	3825.283	J2	0.5334135	3.825283	J2	53.34135	J2
K	2281770.0	5966.077	K	2.2817700	5.966077	K	228.17700	K
L1	3062672.0	7555.257	L1	3.0626720	7.555257	L1	306.26720	L1
L2	1447559.0	5870.040	L2	1.4475590	5.870040	L2	144.75590	L2
M1	1035823.0	5259.086	M1	1.0358230	5.259086	M1	103.58230	M1
M2	716631.0	4554.301	M2	0.7166310	4.554301	M2	71.66310	M2
N	655340.9	3608.502	N	0.6553409	3.608502	N	65.53409	N
O	1338276.0	7084.771	O	1.3382760	7.084771	O	133.82760	O
TOTAL	29051511.2			29.0515112			2905.15112	

*Data Generated and Compiled by:
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Indian Space Research Organization (ISRO)
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Table-2: Area and perimeter of various blocks of Keoladeo National Park generated using GPS based Mobile Mapping Unit

4.3 Signature study

Backscattering coefficient values for various wetland habitats and different components of wetland ecosystem were extracted from all the SAR images, which have been used at appropriate places while analyzing the data and images during interpretation. Various digital image processing tools like principal component analysis, data fusion techniques, IHS to RGB and RGB to IHS conversions, separability analysis, SAR texture analysis, and SAR polarimetric techniques were applied to appropriate data sets where ever required to enhance the potential of Radar data in wetland studies.

5.0 RESULTS AND DISCUSSION:

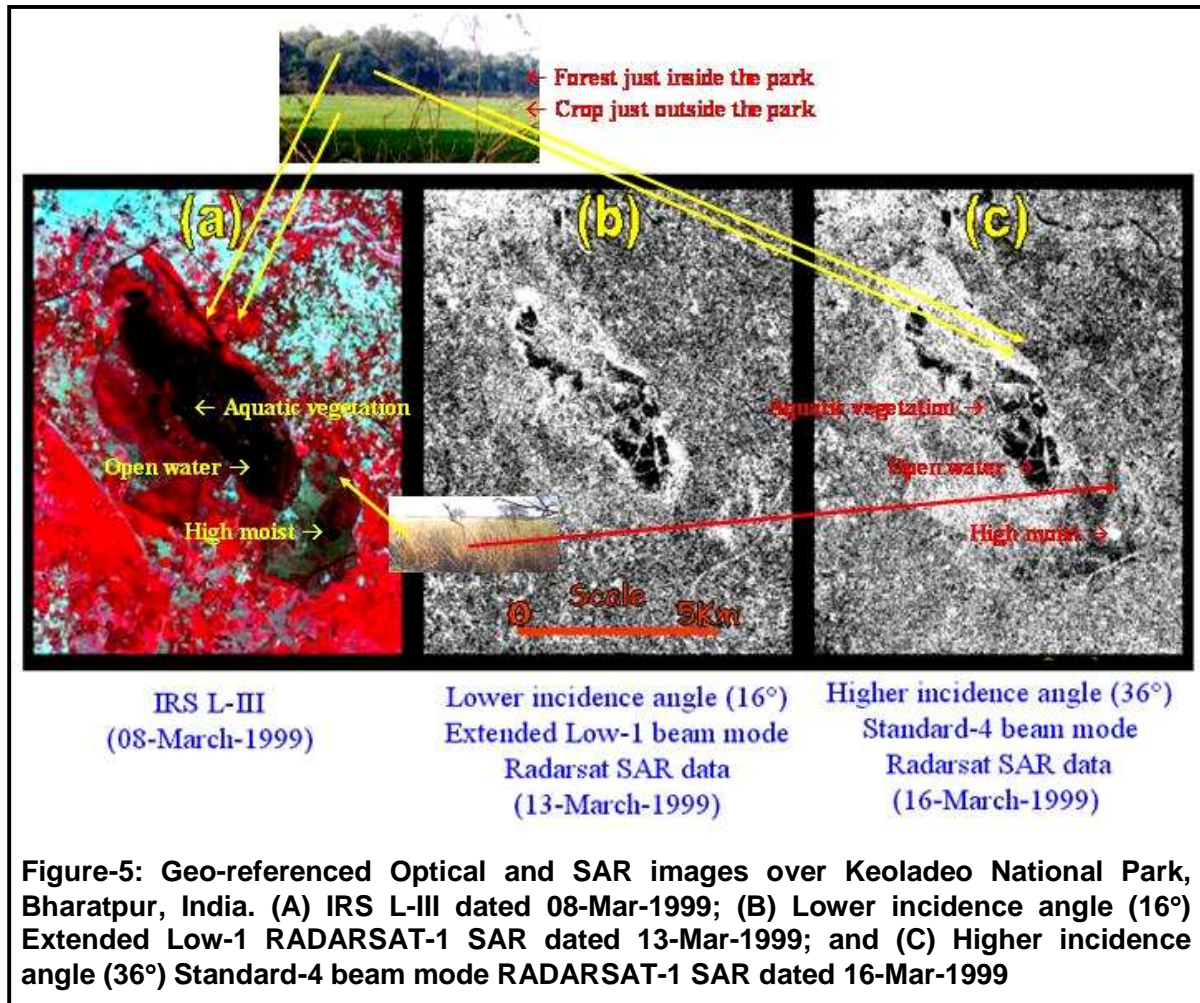
In order to describe the explored application potentials of Synthetic Aperture Radar (SAR) data sets acquired at different sensor parameters, results have been discussed from the following seven different perspectives:

1. Use of Multi-incidence angle SAR data in wetland inventory
2. Use of Multi-polarized SAR data in wetland inventory
3. Use of Temporal SAR data in wetland inventory (Change detection)
4. Use of High resolution single look SAR data in wetland inventory (SAR texture analysis)
5. Use of Multi-frequency SAR data in wetland inventory

6. Use of Interferometric Coherence SAR data in wetland inventory (Use of SAR under adverse weather and windy conditions)
7. Use of Polarimetry Interferometry (PolInSAR) coherence in wetland inventory.

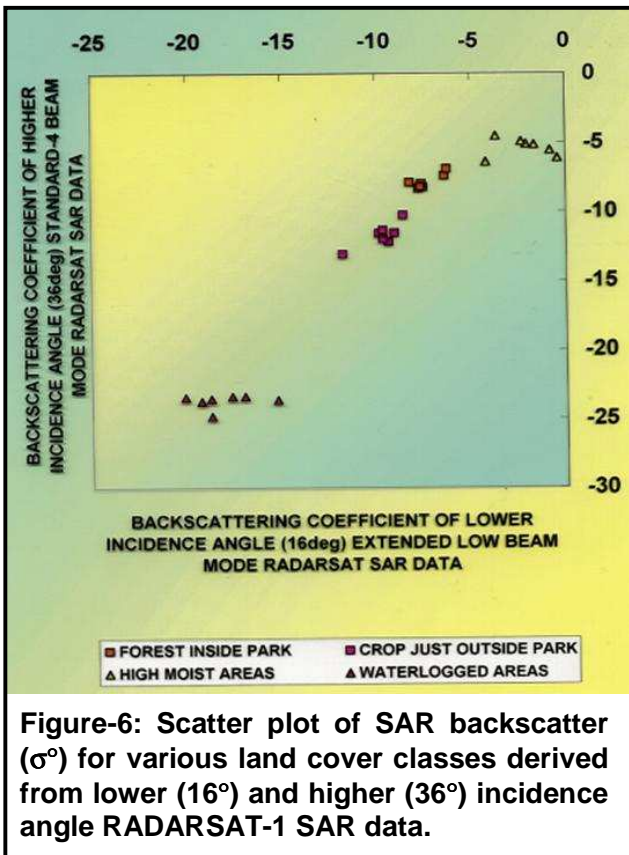
5.1 USE OF MULTI-INCIDENCE ANGLE SAR DATA IN WETLAND INVENTORY

The geo referenced and enhanced satellite data from optical and Radar sensors showing Keoladeo National Park are shown in **Figure-5**. **Figure 5 (a)** shows sub image of IRS L-III. **Figure-5(b)** and **Figure-5(c)** shows lower (16°) and higher (36°) incidence angle RADARSAT-1 SAR data covering Keoladeo National Park acquired on



13-Mar-1999 and 16-Mar-1999. In IRS L-III image, the wetland habitat is seen in dark tone and the vegetation in various tones of red. The barren areas are cyan in colour. Interpretation of IRS L-III image suggests that at few places, there are similarities in tones between land covers outside and inside the park. It was also found to be less sensitive to distinguish open water habitat from the aquatic vegetation locality and areas of high soil moisture content. Thus, very few themes useful for a wetland inventory can be distinguished from the optical image. Comparison of lower (16°) and higher (36°) incidence angle RADARSAT-1 SAR images acquired through Extended Low-1 (EL1) and Standard (S-4) beam modes and shown in **Figure-5(b)** and **Figure-5(c)**, indicates better identification of various wetland themes in higher (36°) incidence angle RADARSAT-1 S-4 SAR data. The thematic classes include open water habitat, aquatic vegetation inside the lake, forest area, crop area just outside the park and high soil moisture areas. The better differentiation in higher incidence angle SAR data is due to the greater sensitivity of higher incidence angle SAR data towards the texture of vegetation cover and surface roughness of reflecting surfaces (Henderson, et. al., 1998; Ulaby, et. al., 1990).

Figure-6 shows the scatter plot of SAR backscatter (σ°) acquired at lower (16°) and higher (36°) incidence angle RADARSAT-1 SAR data for different thematic classes. **Figure-6** indicates that thematic classes like crop areas just outside the park and the forest areas just inside the park, which were mixing at few places on IRS L-III FCC and were also not very clear on lower (16°) incidence angle SAR data, are clearly differentiable in higher incidence (36°) SAR data (Srivastava, et. al., 2001a). **Figure-6** also indicates that high soil moisture localities are readily differentiable on both lower and higher incidence angle SAR data sets, whereas these classes are completely mixing with each other on IRS L-III FCC.



Comparison of IRS L-III FCC and RADARSAT-1 S-4 image indicates that at some places inside the park, optical data provides better delineation between land cover classes. For example at the south-eastern part of the park, park boundary is more prominent in IRS L-III image as compared to RADARSAT-1 S-4 image. It suggests that in order to fully exploit the strength of satellite remote sensing data in wetland inventory, optical remote sensing data should also be used along with Radar data. Similar observation has been reported by many other researchers worldwide. For example, Toyra, et al., (2002) have demonstrated with the help of RADARSAT-1 SAR and SPOT scenes that the information from radar and visible/infrared satellite imagery is complementary and that flood mapping in wetland areas can be achieved with higher accuracy if the two image types are used in combination. Similarly, Milton, et al., (2003) utilized triplets of RADARSAT-1 images with Landsat-7 images in a multi-sensor and

multi-temporal approach to delineate and classify wetlands and their vegetative communities. In order to evaluate the role of combined data set, Radar data is fused with IRS L-III data. Fusion is performed by converting Red,

Green and Blue image channels of IRS L-III FCC to IHS (Intensity, Hue and Saturation) image channels. After RGB to HIS transformation, the Intensity channel has been replaced by the SAR image and then IHS channels is transformed again to RGB (Red, Green and Blue), resulting in fused product of optical and SAR data. The fused products are shown in **Figure-7**. From **Figure-7(a)** and **Figure-7(b)** it is clear that the IRS L-III data fused with higher incidence angle RADARSAT-1 S-4 data is superior to IRS L-III data fused with lower incidence angle RADARSAT-1 EL-1 data. A closer examination of the image reveals that the human eye can distinguish these classes due to textural differences rather than spectral effect. Thus instead of just using the popular digital classification techniques used to distinguish spectral classes, it is more useful to apply textural classifier approach to fully exploit the potentials of SAR in wetland inventory. Section 5.4 of this article describes the textural classification approach.

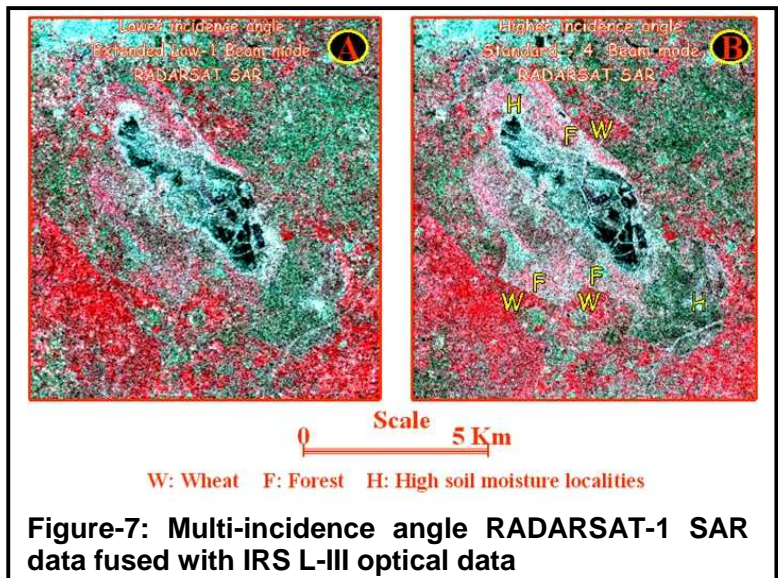


Figure-8 depicts the aquatic vegetation and open water habitat as derived from maximum likelihood classified IRS L-III and higher incidence angle RADARSAT-1 S-4 data respectively. It is clear from **Figure-8** that, extent

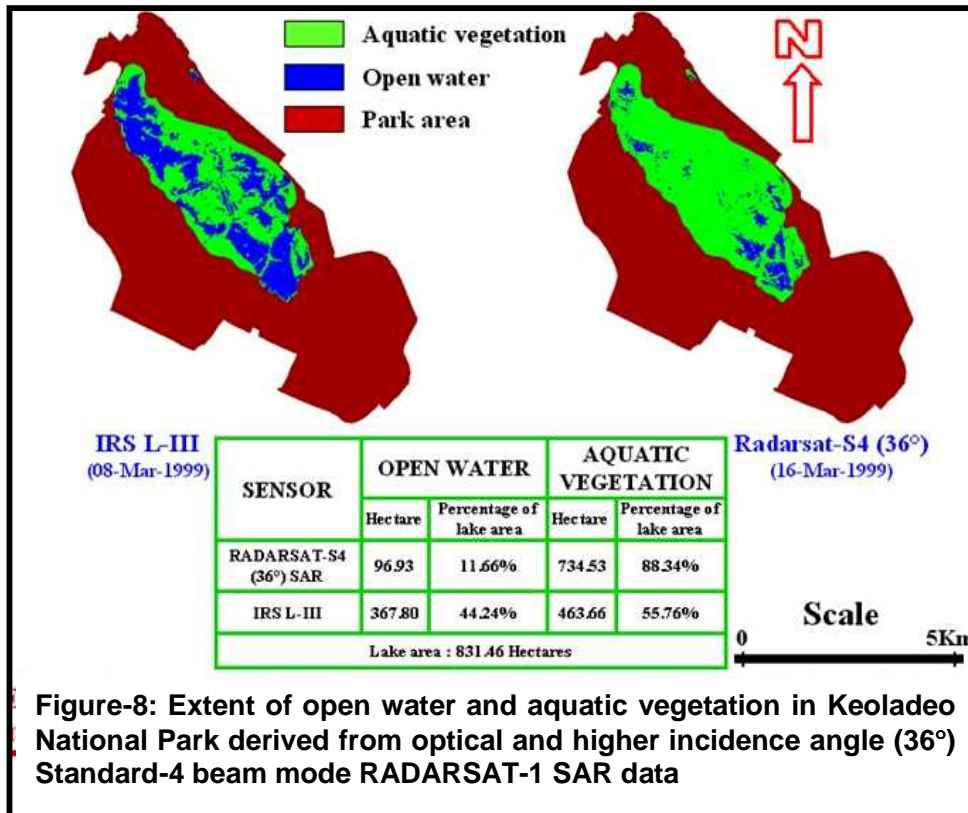


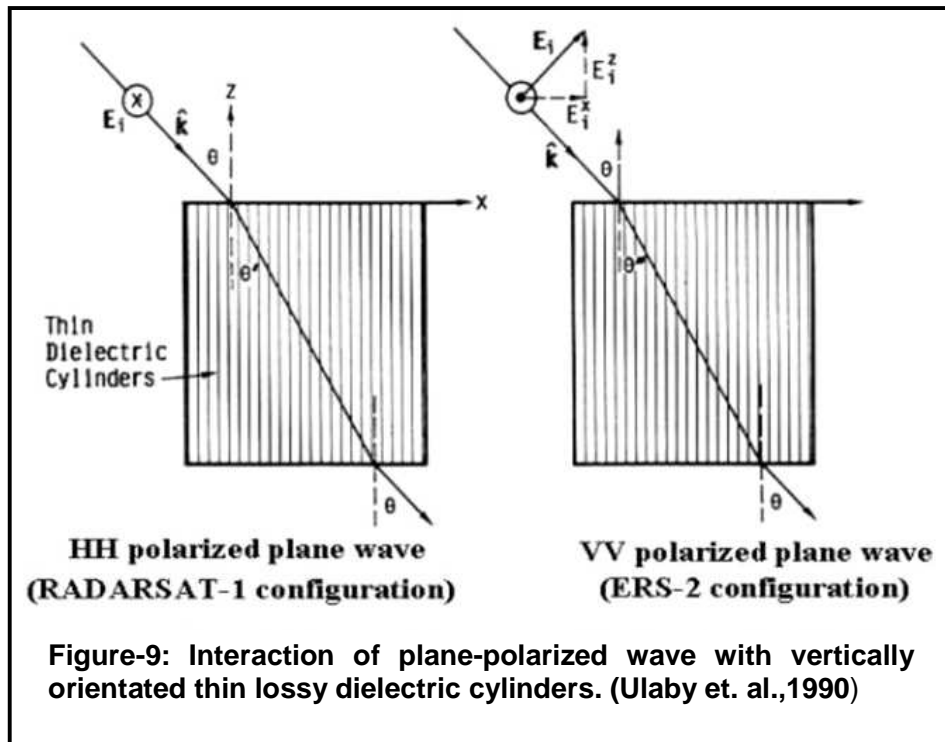
Figure-8: Extent of open water and aquatic vegetation in Keoladeo National Park derived from optical and higher incidence angle (36°) Standard-4 beam mode RADARSAT-1 SAR data

of open water habitat is over-estimated in optical data. The over-estimation is nearly four times to that of RADARSAT-1 S-4 data, as shown in **Figure-8**. Over-estimation of extent of open water habitat in optical data is attributed to poor spectral separability between open water habitats and the aquatic vegetation zone and high soil moisture localities. In contrast, to this, the higher incidence angle RADARSAT-1 S-4 data very clearly shows not only the open water habitat but also the network of roads, dams and other linear features. It is shown that while only 55.76% of the lake area is classified as aquatic vegetation in IRS L-III image, the RADARSAT-1 S-4 data shows it to be 88.34%. This remarkable difference in estimate is mainly due to the ability of high incidence angle RADARSAT-1 SAR data to distinguish correctly the open water habitat due to the extreme smoothness of water surfaces particularly at higher angle of incidence. It has been verified by the park authorities that the result obtained from SAR data appears close to reality. Different species of birds use different habitat for breeding and feeding. Therefore quantitative information on open water and aquatic vegetation has a direct impact on the assessment of area available to different bird species and waterfowls. Apart from this the quantitative information is also useful for deciding the amount and location of area from where aquatic vegetation needs to be removed. This information is very critical for park authorities to allocate funds to remove the aquatic vegetation as a weed control measure.

5.2 USE OF MULTI-POLARIZED SAR DATA IN WETLAND INVENTORY

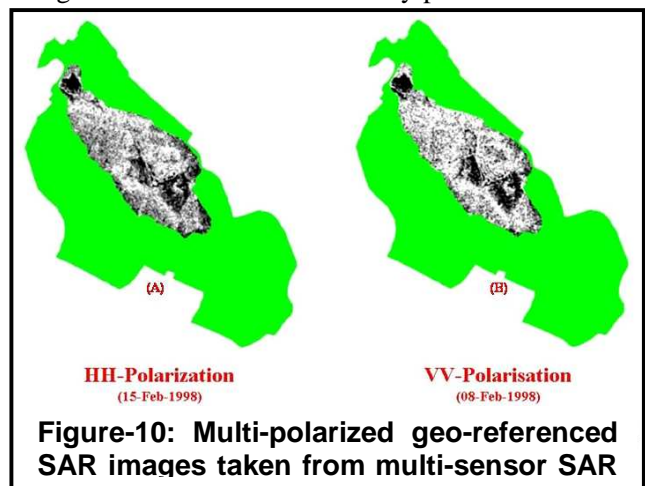
In the study area, the aquatic vegetation mostly consists of vertically oriented tall grasses. For the incident microwave signal, these grasses act as the assembly of vertically oriented thin lossy dielectric cylinders and can be treated as oriented volume over ground (OVOG). The orientation of these lossy dielectric cylinders plays an important role in determining the polarization behaviour of backscatter signal. To understand the effect of orientation of grasses to the incident polarized signal, to begin with one can assume the grasses to be vertically oriented thin lossy dielectric cylinders with its diameter less than the wavelength of the incident wave. **Figure-9** illustrates the interaction of incident wave with thin cylinders when the cylinders are oriented in vertical direction.

When the cylinder's diameter is much smaller than the wavelength ($\lambda = 5.6$ cm) of the microwave signal, it couples strongly with the incident wave when the electric field vector of the incident wave is parallel to the axis of the



lossy dielectric cylinders (which is the case for vertically polarized wave, VV) at a given angle of incidence. Similarly, when electric field vector of the incident wave is orthogonal to the axis of the lossy dielectric cylinders (which is the case for horizontal polarization HH), it couples poorly to the lossy dielectric cylinders resulting in lower value of radar backscatter as compared to the radar backscatter of vertically polarized (VV) wave. This explains the basic interaction mechanism of linearly polarized incident wave to the vertically oriented thin dielectric cylinders.

The polarization behavior of the SAR signal is affected by the size shape and orientation of the canopy being illuminated. It was felt that a thin lossy dielectric cylinder would be an appropriate representation of grasses whereas the open water could be assumed as a large flat surface. When a beam strikes a large flat surface, it would have equally high horizontally and vertically polarized backscatter. For the case of grasses with oriented volume over ground (OVOG) in vertical direction, there is higher interaction with vertically polarized wave due to vertical component of electric field vector E_i^z ($E_i^z = E_i \sin\theta$) resulting in strong coupling. This would result in higher radar backscatter for vertically polarized waves and a lower radar backscatter of horizontally polarised waves. The reverse is true in case of grasses, which are lodged. Hence, in case of grasses, the orientation of grasses with respect to the radar beam determines as to whether the strength of horizontal or vertical polarized wave would be more as per the detailed discussion on polarization behaviour of Radar return as discussed earlier. In contrast to the case of oriented volume over ground (OVOG) as the case with vertically oriented tall grasses in Keoladeo National Park, the wave propagation through the vegetation volume with random volume over ground (RVOG) is independent of the polarization state of the wave. Thus the wave propagation in case of random volume over ground (RVOG) is polarimetric isotropic and does not provide polarization preferential signatures like the case of oriented volume over ground (OVOG).



To study the impact of polarization on wetland targets, SAR data from two satellites namely ERS-2 and RADARSAT-1 was used. Both the sensors operate at C-band. ERS-2 SAR operates at VV polarization where as RADARSAT-1 operates at HH polarization. The central angle of incidence was 23° for ERS-2. Hence Standard-1

(S1) Beam mode data, at local incidence angle close to 23° was used for the study. This pair of ERS-2 and RADARSAT-1 S-1 SAR data ensured that except for the polarization, all the other sensor parameters namely frequency and incidence angle were identical. **Figure-10** shows the RADARSAT-1 Standard-1 beam mode SAR

data acquired on 15-Feb-1998 and also the ERS-2 SAR data acquired on 08-Feb-1998 over Keoladeo National Park, Bharatpur, India. In case of open water habitat, the polarization of incoming wave becomes insignificant as water being a very smooth surface, whatever is the polarization, the total energy is reflected off in a direction opposite to the SAR sensor. This results in low return at both VV as well as HH polarization. This fundamental interaction mechanism of microwaves to a specific target was exploited to extract the information of wetland habitat. Wherever vertical aquatic vegetation exist, the VV polarized data from ERS-2 yielded higher backscatter as compared to that of HH polarized data from RADARSAT-1. Wherever lodged grasses exists, the VV polarized data from ERS-2 yielded lower backscatter as compared to that of HH polarized

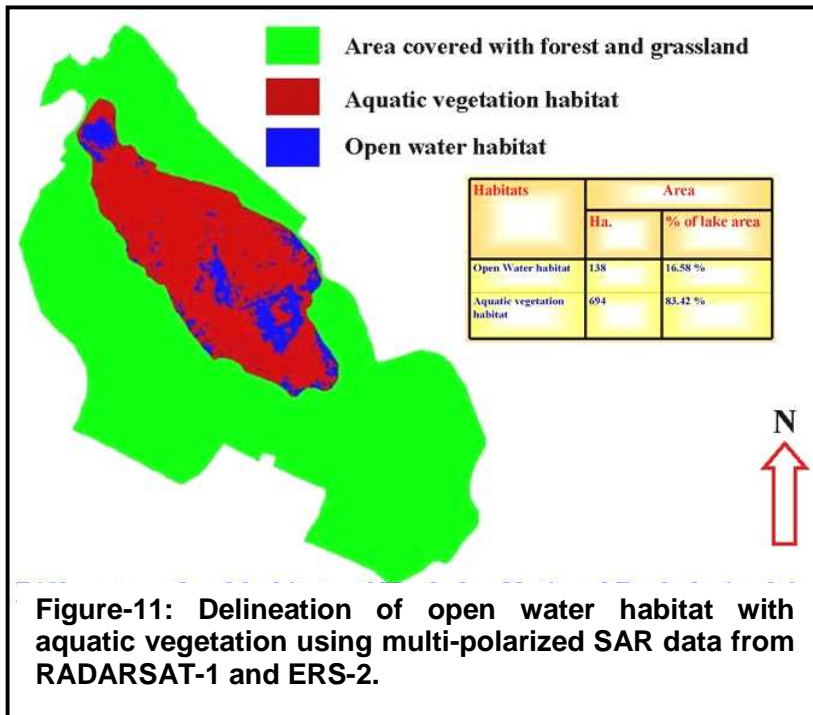


Figure-11: Delineation of open water habitat with aquatic vegetation using multi-polarized SAR data from RADARSAT-1 and ERS-2.

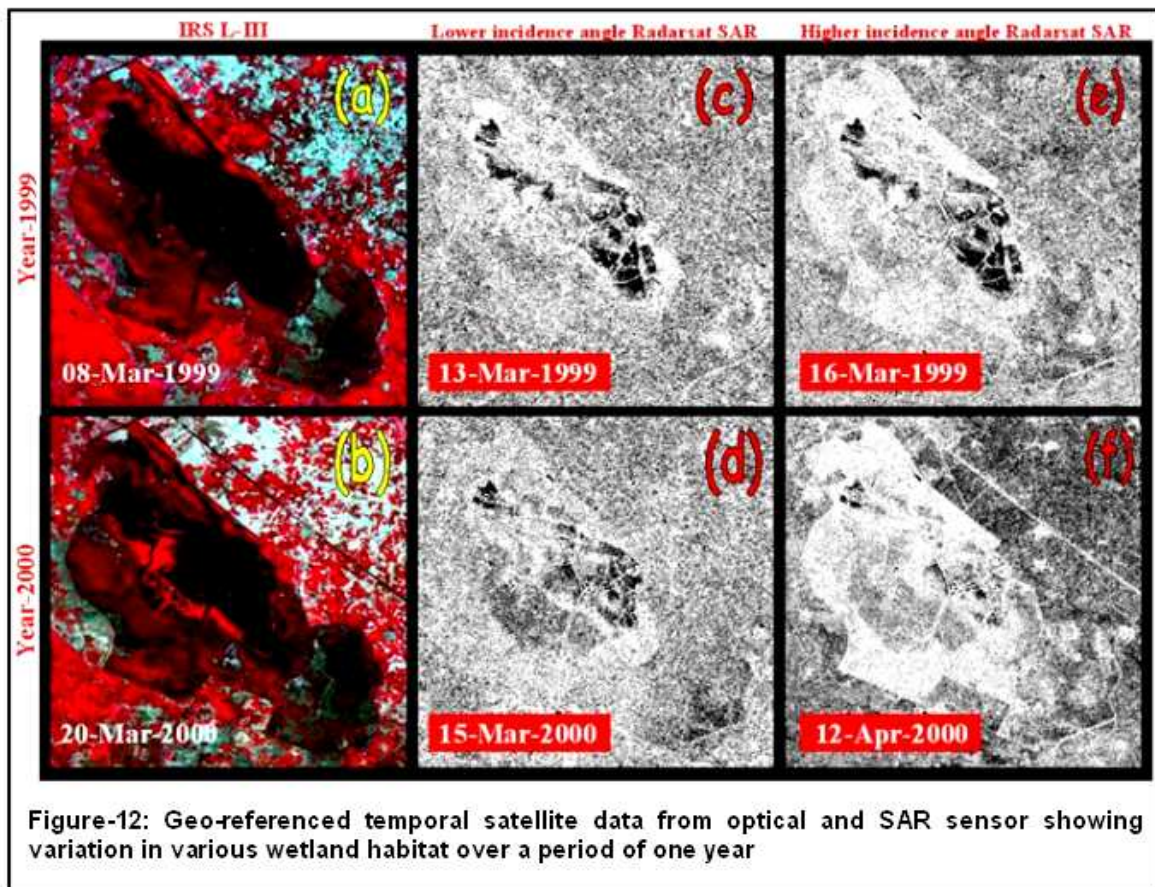
data from RADARSAT-1 where as in case of open water both ERS-2 as well as RADARSAT-1 gave lower radar backscatter. Thus it was felt that ratio of VV (ERS-2) to HH (RADARSAT-1) polarized SAR images be examined to delineate aquatic vegetation from open water habitat (Srivastava, et al., 2002b).

When the ratio of VV (ERS-2) to HH (RADARSAT-1) polarized image was studied (**Figure-11**), it was observed that the areas having grasses showed higher difference as compared to that of open water. Thus, difference of the VV to HH polarized images was successfully used to delineate aquatic vegetation from open water habitat. It was observed that out of the total lake area of 8.32 Km², only 1.38 Km² or 16.58 % area was under open water habitat whereas rest 6.94 Km² or 83.42 % of the lake area was under aquatic vegetation.

5.3 USE OF TEMPORAL SAR DATA IN WETLAND INVENTORY

The geo-referenced and enhanced temporal satellite data sets from optical (IRS, L-III) and multi-incidence angle SAR (RADARSAT-1) sensors over Keoladeo National Park are shown in **Figure-12**. In IRS-1C LISS-III FCC, the wetland habitat is seen in dark tone and the vegetation in various tones of red. The barren areas are cyan in colour. **Figure-12(a) & 12(b)** indicate the changes in various wetland habitats over a period of one year as seen from optical data sets. **Figure-12(c) & 12(d)** and **Figure-12(e) & 12(f)** are showing the variations in different wetland habitats as captured by lower and higher incidence angle RADARSAT-1 SAR data over the time frame close to optical data set. Interpretation of IRS-1C (LISS-III) image suggests that at few places, there are similarities in tones between land covers outside and inside the park. It was also found to be less sensitive to distinguish open water habitat from the aquatic vegetation locality and areas of high soil moisture content. Thus, very few themes useful for wetlands can be distinguished from the image. Comparison of lower and higher incidence angle RADARSAT-1 SAR data shown by **Figure-12(c), 12(d), 12(e)** and **12(f)** indicate better identification of various wetland themes in the higher incidence angle RADARSAT-1 SAR data. The thematic classes include open water habitat, aquatic vegetation inside the lake, forest area, crop area just outside the park and high soil moisture areas.

In order to estimate the variation in different habitats over a period of one year, multi-year Radar FCC were generated for lower and higher incidence angle RADARSAT-1 SAR (**Figure-13**). Red colour was assigned to



1

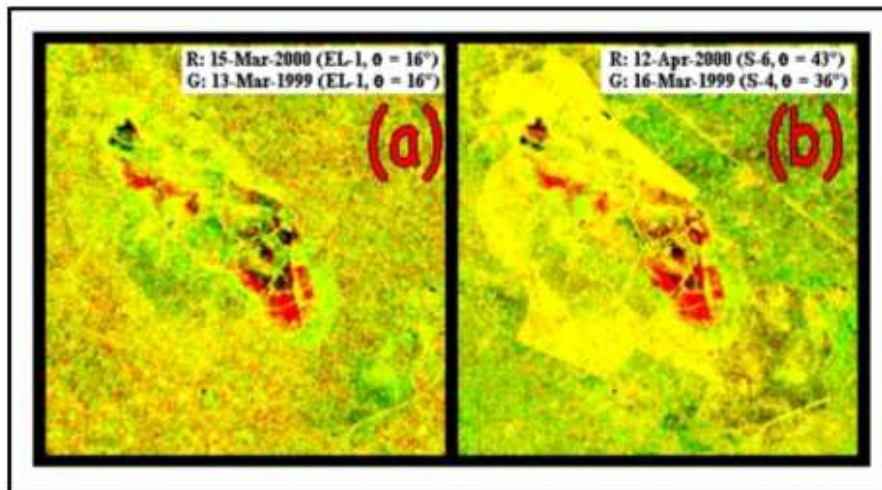


Figure-13: Change in extent of open water habitat over a period of one year. Red colour in (a) highlights the area that was under open water habitat in year-1999 whereas in the year-2000 these areas are under aquatic vegetation.

year-2000 images whereas year-1999 images have been assigned green colour. Since open and smooth water gives dark signature on SAR image and aquatic vegetation gives bright signature (due to corner reflector effect) on SAR image (Ulaby, et. al., 1990), decrease in open water habitat in the year-2000 is seen in red tone in **Figure-13** (Srivastava, et al., 2001b). Thus the dynamics of water and vegetation, which often constitute the underlying cause for the observed patterns of species diversity and habitat use, are clearly discernible using temporal SAR data. Moreover, due to the uncertainty of availability of optical data for the desired time periods, a clear elucidation of patterns and linkages between hydrology and aquatic vegetation is difficult using optical remote sensing data. Therefore, the use of radar data is clearly advantageous and would have considerable applied value. Use of temporal Radar data has been utilised to capture the temporal changes in wetland dynamics due to

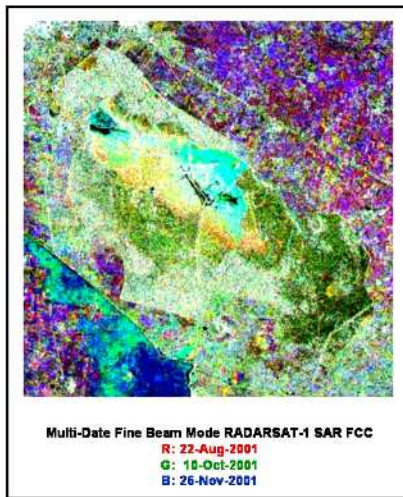


Figure-14: SAR FCC generated from high resolution Fine beam mode RADARSAT-1 temporal SAR data covering rainy to winter season

change in water availability and other climatic conditions with time. For example, Karszenbaum, et. al., (2007) have exploited multi-temporal ENVISAT-1 ASAR data by combining October image (spring and normal water in rivers), November image (spring and a strong increase in water level) and March image (autumn starts) to capture major differences in wetland area over lower delta of Parana river, close to Buenos Aires City. Similarly, Bartsch, et al., (2004) have exploited the high temporal resolution of ENVISAT ASAR wide swath data for the detection of seasonal, intermittent and permanent inundation patterns in central Siberia. In fact, potential of uninterrupted supply of Radar data to capture the temporal variations in a wetland ecosystem can help in devising location specific management tasks such as the removal of aquatic vegetation, deepening and de-silting of important habitats. Moreover, temporal changes are good indicators for predicting the expected species richness of the seasonal migrant bird species. This in turn, has an impact on eco-tourism. The cumulative data on the dynamics of habitat would go a long way in formulating system models of not only habitat but on the expected species richness. Due to all weather capability of Radar data along with its unique sensitivity towards the texture of

imaging terrain and its ability to delineate the open water habitat with aquatic vegetation, the landscape level interactions of the wetland habitats is relatively easier to model using SAR data than through the conventional optical remote sensing approaches.

An attempt was made to study the dynamics of changes in various wetland habitats starting from the rainy season. Four images of fine beam mode RADARSAT-1 SAR acquired in the month of August (22-Aug-2001), October (10-Oct-2001), November (26-Nov-2001) and January (13-Jan-2002) were analyzed for this purpose. An intensive image processing of the data using EASI/PACE, software, enabled the identification of following four classes of wetland (Srivastava, et al., 2006b):

- a) Open water in August
- b) Open water habitat overgrown with aquatic vegetation in October and November.
- c) Aquatic vegetation with water underneath at all times (August to November)
- d) Senescent stages of aquatic vegetation on elevated land surface surrounding the open water and partially submerged vegetation.

A time composite of August (Red-band), October (Green-band) and November (Blue-band) data as shown in **Figure-14** further fortified the interpretation. This exercise conclusively shows the enormous benefits that can be reaped by the use of Radar data for wetland conservation and management on a wider scale in the monsoon climate countries in Asia and elsewhere. Study indicated that the data of August month has played critical role in identification of various components and classes important for birds and waterfowls. Use of August data highlighted the role of SAR data for assessment, monitoring and management of a wetland ecosystem as it ensures uninterrupted availability of Satellite SAR data during the monsoon season. Inclusion of monsoon data in the temporal analysis leads to delineation of more number of wetland habitats that are important for birds. The feasibility of information extraction using temporal SAR data is of great significance to wetland researchers in

formulating Habitat Suitability Index (HSI) models for a variety of faunal species including local migrant bird species.

5.4 USE OF HIGH RESOLUTION SINGLE LOOK SAR DATA IN WETLAND INVENTORY (SAR TEXTURE ANALYSIS)

In reference to SAR data, texture is defined as a measure of degree of coarseness. There can be various types of textural measures depending upon how they are generated from G.L.C.M. Texture measures are evaluated using a G.L.C.M. or a G.L.D.V. and are based on second order statistics. They can be evaluated either in a directional form or as an invariant. G.L.C.M. stands for Gray Level Co-occurrence Matrix whereas G.L.D.V. stands for Gray Level Difference Vector. In order to exploit the textural properties of single look high resolution SAR data, following 13 texture measure images were generated for SAR data of all the four dates used in this part of the analysis:

1. Homogeneity
2. Contrast
3. Dissimilarity
4. Mean
5. Standard deviation
6. Entropy
7. Angular second moment
8. Correlation
9. GLDV angular second moment
10. GLDV entropy
11. GLDV mean
12. GLDV contrast
13. Inverse difference

From the total 56 input channels, principal component analysis was performed. Four Principal components namely PC1, PC2, PC3 and PC4 were generated from 13 texture measures channels available for all the four months (**Figure-15**). Out of four principal components generated for all the four months, the most informative principal component was selected. The most informative principal component channel for August & October and November & January have been classified and two classified outputs were generated for 22-Aug-2001 & 10-Oct-2001 data set and for 26-Nov-2001 & 13-Jan-2002 data sets. Finally these two outputs were merged to obtain the final classified output of Keoladeo National Park. The overall methodology adopted in the study is given in **Figure-16** (Srivastava, et al., 2005). Results of the study indicated that the number of classified classes and classification accuracy of various components and various habitats of Keoladeo National Park increased considerably by adopting the approach followed in the analysis as compared with the classification accuracy and classified classes with single channel temporal SAR data. Study indicates that the data of August month, which falls in rainy season, has played critical role in identification of various components and classes important for birds and waterfowls. Significance of use of August data highlighted the role of SAR data for assessment, monitoring and management of a wetland ecosystem as it assures uninterrupted availability of Satellite data even during the monsoon (rainy) season.

5.5 USE OF MULTI-FREQUENCY SAR DATA IN WETLAND INVENTORY

Difference in penetration depths of various microwave bands due to difference in their wavelengths as discussed earlier in this article can be exploited to retrieve critical information about various wetland habitats. In order to exploit the potential of multi-frequency SAR data in wetland inventory, DLR airborne Experimental SAR (E-SAR) data acquired over Keoladeo National Park in C, L and P bands at higher incidence angles have been analysed. Due to higher incidence angle C-band data which has relatively shorter wavelength as compared to L and P bands, and in turn lesser penetration depth, is not able to fully penetrate the aquatic vegetation and therefore all the wetland area covered with aquatic vegetation appears in brighter tone as compared to open water habitat,

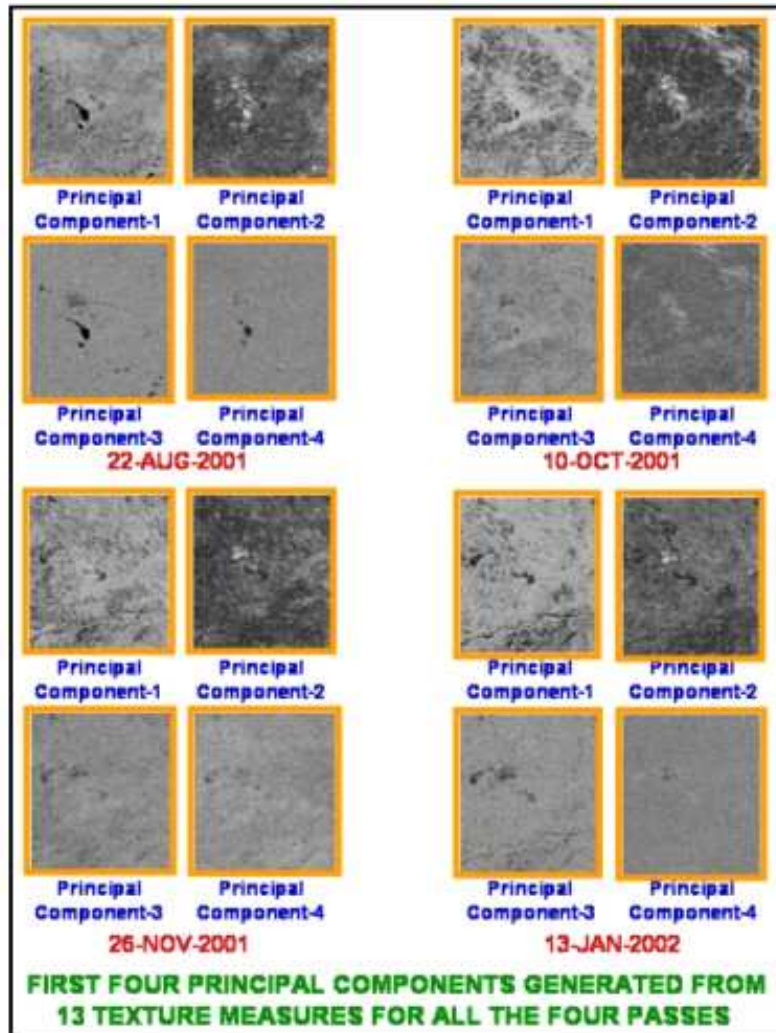


Figure-15: Principal Component Analysis applied on Texture Measures for all the four passes including the rainy season

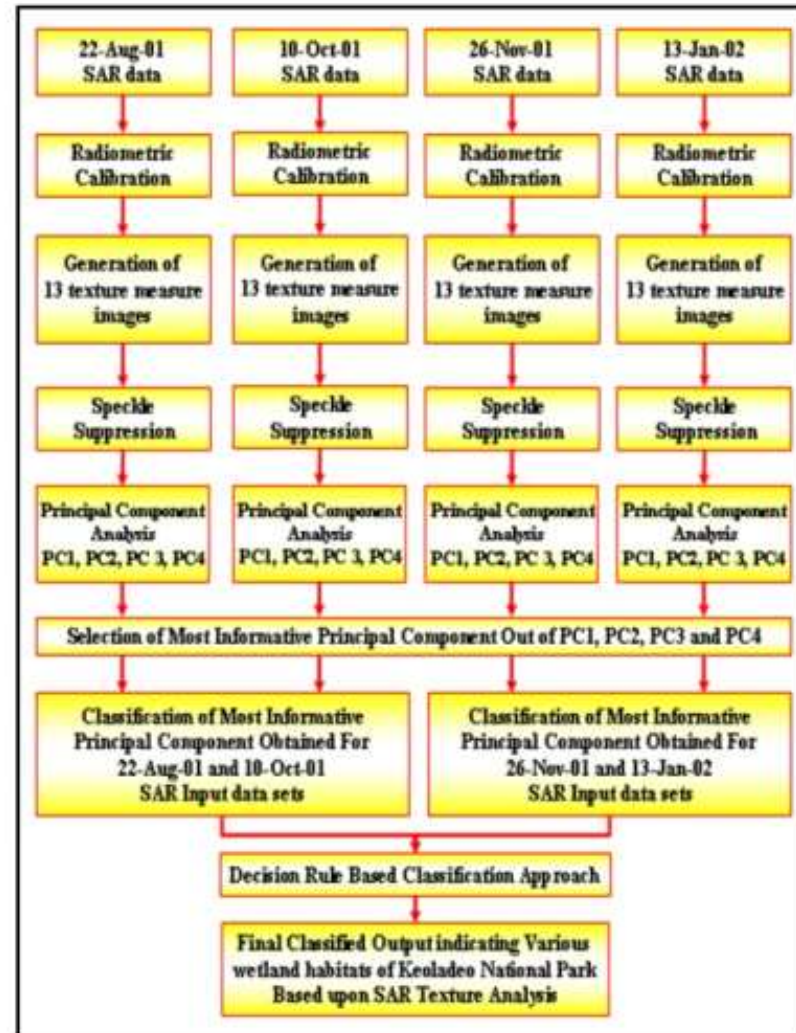


Figure-16: Overall methodology adopted for the classification of various wetland habitats of Keoladeo National Park using SAR texture analysis

which produces dark tone on the SAR image due to specular reflection of the Radar signal. L-band which has longer penetration depth as compared to C band but shorter penetration depth as compared to P band is able to penetrate the layer of aquatic vegetation that has medium thickness. Since medium thick aquatic vegetation is nearly transparent for L band, L band is able to reach below the medium thick aquatic vegetation. If there is no standing water then L band can detect the moisture status of the underneath soil. On similar lines, P band is able to gather information below the very thick and dense aquatic vegetation. Hence, if we combine the results obtained from all the three bands (C, L and P) then it is possible to gather very detailed information about various wetland habitats. A false colour composite generated with C, L and P bands acquired from DLR E-SAR supports the results described in this section. A visual interpretation of the false colour composite is able to delineate open water habitat with aquatic vegetation and is also able to discriminate between various aquatic vegetation classes with varying thickness and densities along with the status of water logging / soil moisture below the vegetation. A comparative evaluation of C and L band at higher angle of incidence and at VV, VH and HV/VH polarization over Velavadar blackbuck sanctuary, Bhavnagar, Gujarat indicated that L-band SAR data acquired at cross polarization is far superior than L-band data acquired at like polarization as well as C-band data at all the polarizations (Srivastava, et. al., 2006c; Patel, et al., 2006a). Effect of multi-parametric SAR data acquired from DLR Experimental SAR at C, L and P bands and at all the four polarizations confirms the capability of longer wavelengths to extract the information about the status of soil moisture underneath the thick vegetation (Srivastava, 2007a).

5.6 USE OF INTERFEROMETRIC COHERENCE SAR DATA IN WETLAND INVENTORY (Use of SAR under adverse weather and windy conditions)

The various demonstrated applications of multi-parametric SAR backscatter, describes the potentials of SAR in wetland inventory. However there are also difficulties associated with use of SAR backscatter due to its sensitivity to wind induced roughness on water surface. The detection and mapping of surface water on SAR imagery is due to the extreme smoothness of water bodies at microwave frequencies. Surface water features are detectable on Radar backscatter image due to the high contrast between the smooth water surface and rough land surface. This fact indicates that in case of windy conditions, interaction of microwave signals to a wind induced rough water surface, are similar to interactions with a rough (land) surface. Due to this reason, at times under adverse weather and windy conditions, it is difficult to differentiate the surface water bodies from the surrounding areas due to wind induced surface waves on the water surface. The dramatic effect of wind on sensitivity of SAR backscatter towards surface water is clearly visible in **Figure-17**.

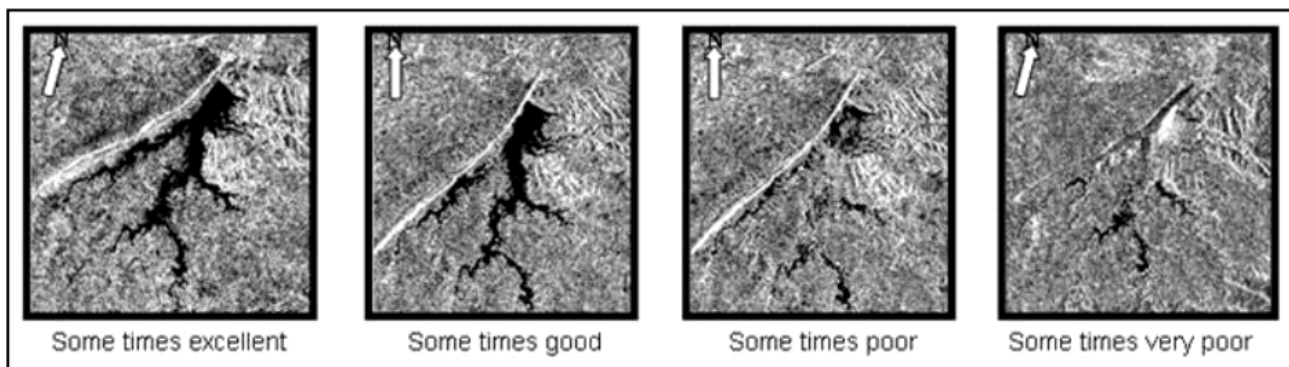


Figure-17: Dramatic effect of wind on Surface water extent as seen on SAR imagery!

In order to overcome this limitation, potential of Interferometric coherence is explored to delineate surface water bodies even under windy conditions (Srivastava et al., 2006d). This is achieved by exploiting the interferometric coherence, which is defined as the normalized complex cross-correlation of both complex signals S_1 and S_2 received from first and second image. The coherence γ is a quantitative measure that represents the amount of noise present in a SAR interferogram. Absolute value of coherence varies from 0 (incoherence) to 1 (perfect

coherence). Coherence value equal to 1 represents that both the signals are identical whereas zero coherence value represents that both the signals do not correlate. Coherence (γ) is defined as:

$$\gamma = \frac{\langle S_1 S_2^* \rangle}{\sqrt{\langle S_1 S_1^* \rangle \langle S_2 S_2^* \rangle}}$$

[Where: S_1 and S_2 represents the two complex signals, $\langle \rangle$ gives the expectation value and $*$ represents the complex conjugation operator]

In the context of interferometry, coherence represents the phase variance between the two SAR images. Value of coherence indicates the level of change in phase. Coherence provides information on temporal stability and is therefore an important feature for general land cover mapping. Zebker & Villasenor, (1992) and Morley, et al., (1996) examined changes in the behaviour of coherence with different surface types and they observed that temporal coherence is dependant on surface cover type. Temporal de-correlation is caused by those features on ground that produces random dislocation of scatterers between the two passes. Forest cover, vegetation / crop cover, water surfaces and human activities like ploughing etc. are good source of random dislocation of scatterers between the two passes. All these phenomena cause random change in the location of scatterers, between the two passes. These changes can be observed over periods of hours to months. However, for some features like water surfaces and dense forests, changes can occur in a matter of seconds. Since no water surface can remain steady between any given passes, random dislocation of scatterers is considerably high in case of water bodies as compared to other land features, hence water bodies exhibits low InSAR coherence. This leads to better identification and mapping of surface water bodies and surface water extent as seen in **Figure-18**. **Figure-18A** & **Figure-18B** and **Figure-18D** & **Figure-18E**, show the intensity images of two ERS-1/ERS-2 tandem interferometric pairs (14-Apr-1996 and 15-Apr-1996 & 30-Apr-1996 and 01-May-1996). During tandem mission in the year 1996, data acquisition by ERS-1 and ERS-2 were separated by 24 hours. However, currently no such tandem mission is available for fresh data acquisition. In absence of such a tandem mission one can make use of Envisat-1 with separation of 35 days or two consequent Radarsat data separated by 24 days for interferometric applications. However one must bear in mind the possible decorrelation between the two interferometric images arising due to increased time lag. The coherence images generated with the help of phase information of these image pairs are shown in **Figure-18C** and **Figure-18F**. Coherence images clearly delineate the water from its surroundings. This portion of the study provides an excellent case study indicating that the InSAR technique is a very promising tool for mapping surface water extent particularly under adverse weather and windy conditions during monsoon (rainy) season. Hence the potential of SAR data is unmatched for wetland inventory irrespective of the weather, cloudy, rainy or sunlight conditions. From view point of a wetland ecosystem like Keoladeo National Park and many others, SAR Interferometry (InSAR) technique can also be exploited for detection and density mapping of forested areas (Srivastava, et al., 2007b). It is due to the fact that interferometric coherence decreases with increasing forest density as seen in **Figure-19** due to high magnitude of random dislocation of the scatterers between the two SAR passes used as InSAR pair. Output of forest density mapping based upon decision rule based approach is shown in **Figure-20**. However, a close look of **Figure-20** reveals that at few places, due to overlapping in interferometric coherence values, very dense forest category is mixing with water class. This ambiguity can be resolved by including SAR backscatter value of both the passes along with interferometric coherence values. Wegmuller and Werner (1995) suggested that combined use of SAR backscatter and interferometric coherence can improve the capability of SAR data manifold for detection and density mapping of forested areas. In order to appreciate the potential of combined (SAR backscatter + Interferometric coherence) data set, a false color composite has been generated by assigning Red color to Interferometric coherence (γ), Green color to SAR backscatter (σ°) of either image and Blue color to Difference of SAR backscatter values of 1st and 2nd pass ($\sigma_1^\circ - \sigma_2^\circ$) as shown in **Figure-21**. Besides Interferometric coherence, the height information provided by SAR interferometry through interferogram is also a very useful tool to monitor wetlands. For example, Alsdorf, et al., (2000, 2001a, 2001b) have monitored water level changes in a large Amazon lake with space borne radar interferometry and altimeter.

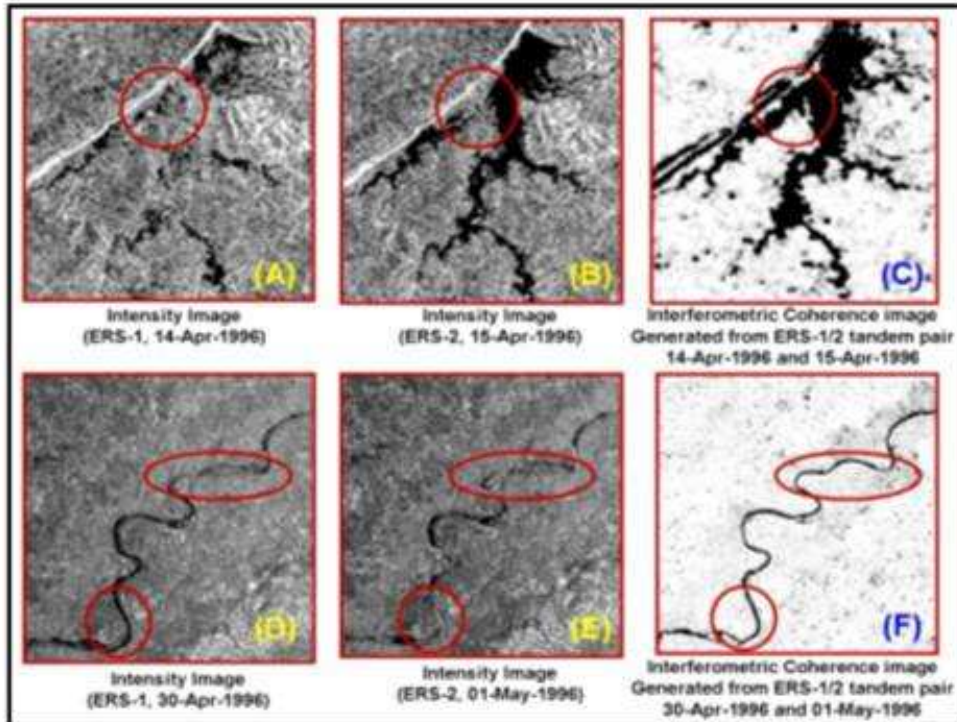


Figure-18: Coherence image and corresponding SAR backscatter image showing better delineation of water bodies in coherence images as compared to backscatter images under adverse weather and windy conditions.

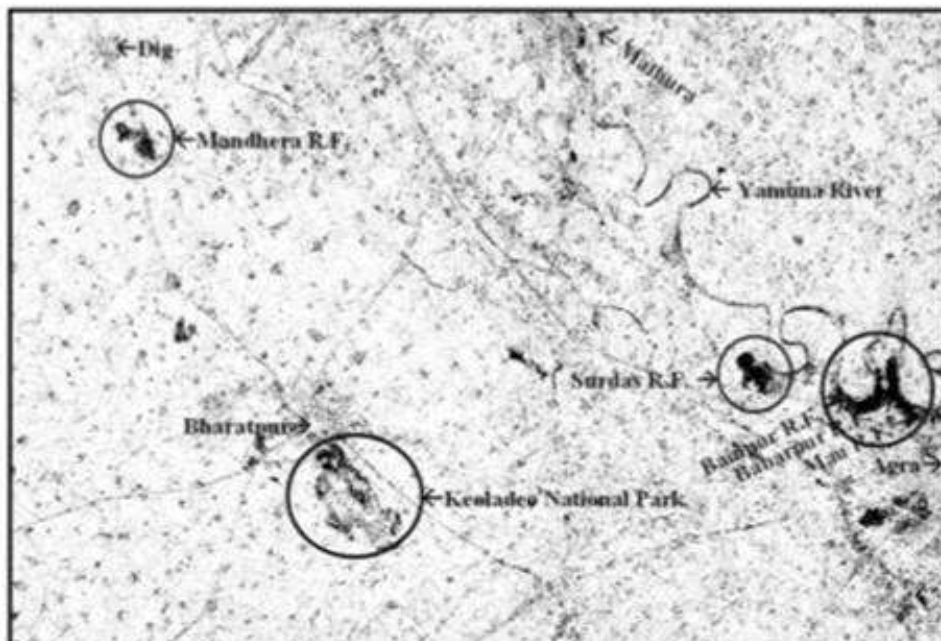


Figure-19: Interferometric Coherence image over parts of Agra, Mathura and Bharatpur districts, showing low values of interferometric coherence for forested area and surface water bodies

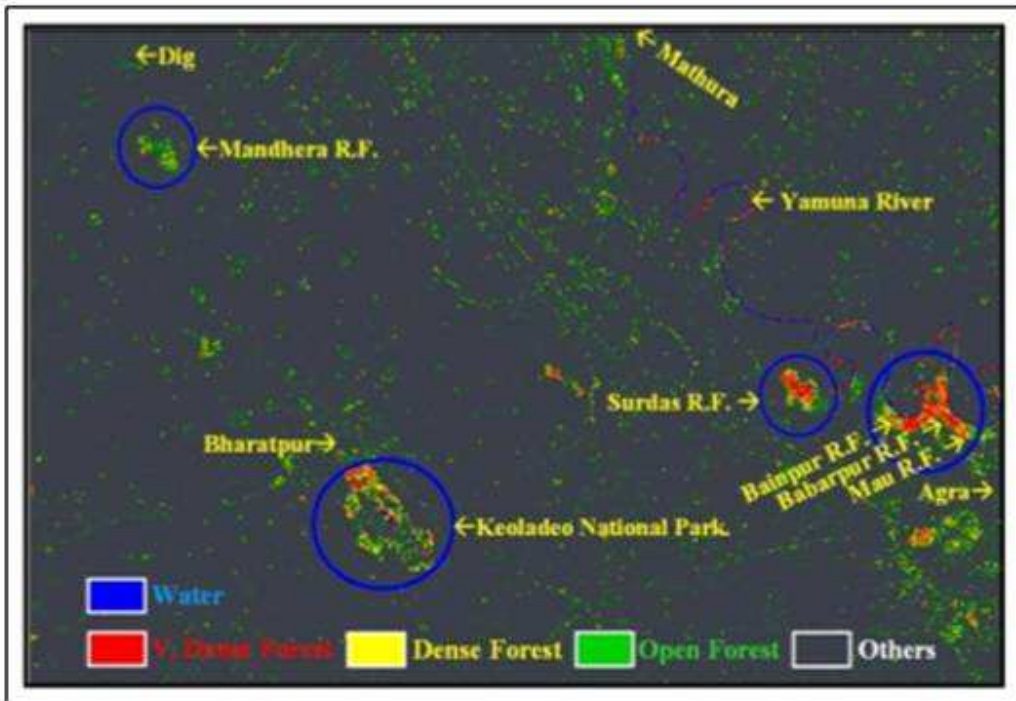


Figure-20: Delineation of forest densities from interferometric coherence image using decision rule based approach. Figure shows that use of InSAR coherence alone can create overlapping at few places between very dense forest category and surface water.

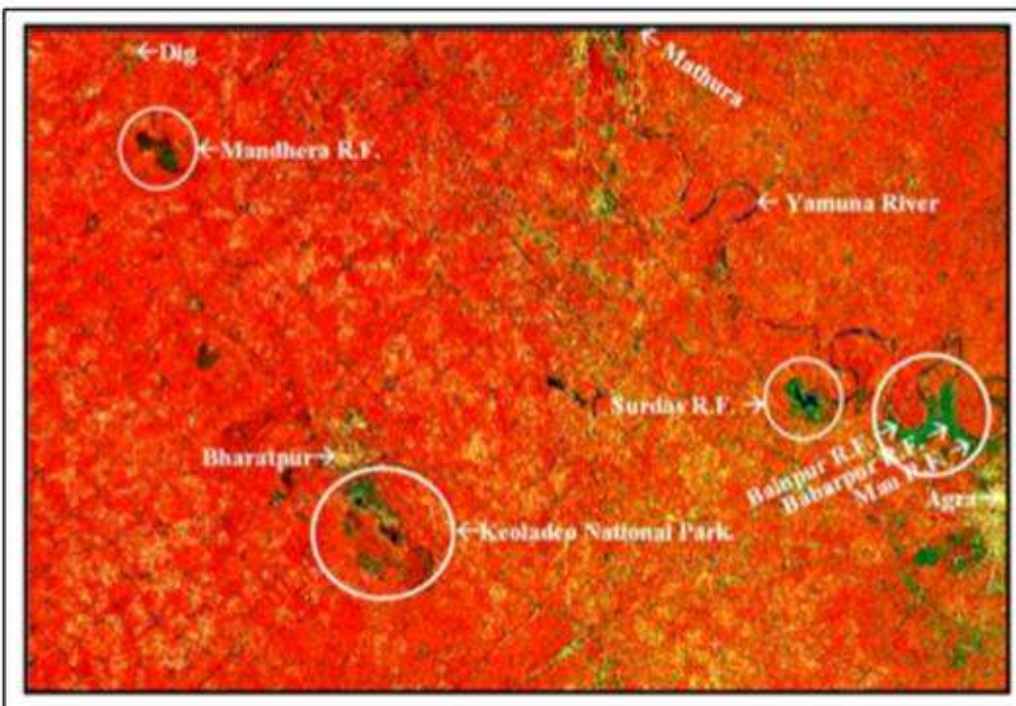
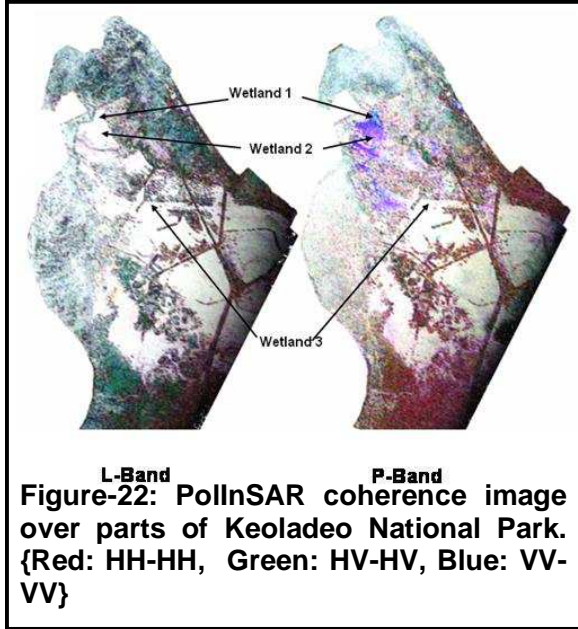


Figure-21: Interferometric false colour composite over parts of Agra, Mathura and Bharatpur districts {Red: Interferometric coherence; Green: SAR Backscatter; Blue: ERS1-ERS2 SAR backscatter}; Forest is seen in different shades of green colour depending upon the forest density whereas surface water is seen either in blue colour or in black colour.

5.7 USE OF POLARIMETRY INTERFEROMETRY (PolInSAR) IN WETLAND INVENTORY

Authors find it appropriate to emphasise that the latest state of the art technology of Polarimetry Interferometry (PolInSAR) should also be explored for its possible potential applications in wetland inventory. From wetland point of view, the distribution of various constituents of the target and its underlying soil condition determine the



phase centre for each polarisation response. With repeat pass fully polarimetric DLR ESAR data, the effect of underlying soil (being flooded/saturated/wet/dry) on variation of PolInSAR coherence was studied. **Figure-22** shows the L and P-band PolInSAR coherence images constructed by assigning red colour to coherence between repeat pass at HH polarization, green colour to coherence between repeat pass at HV polarization and blue colour to coherence between repeat pass at VV polarization.

The grass in wetland area along with condition of underneath soil is a typical natural volume scatterer. Incident wave penetrates volume scatterer and it interacts with the scatterer as a whole. Volume scatterer is characterised by the distribution of scatterers with varying phase centres in a given direction depending upon the polarization state. As a direct consequence, they are affected by geometrical decorrelation in the form of volume decorrelation. The wetland targets at marked locations (wetland1, wetland 2 and wetland 3) in **Figure-22** clearly depict the impact of variation in the underlying soil conditions on coherence at

different polarisations owing to the differences in the phase centres at L and P bands.

Figure-23 shows the variation of SAR backscatter at L and P-bands, along with the PolInSAR coherence at different polarisations for marked locations wetland1, wetland2 and wetland3 in **Figure-22**. One can notice the

striking difference in the backscattering and coherence variation patterns. It can be observed from **Figure-23** that SAR backscatter of the marked wetland areas is not showing much variation amongst themselves at L and P bands at all the four polarisations. A maximum variation of around 3 db between wetland1 and wetland2 is observed for only one case i.e. P-band at HH polarisation. This is attributed to the fact that SAR backscatter is a resultant average response with the different constituents of the target. Thus no inference can be drawn on the variation amongst the different constituents of these wetland targets from the SAR backscatter at different polarisation of P-band or L-band alone. However when one studies the PolInSAR coherence from these targets, while one can observe consistent high PolInSAR coherence values

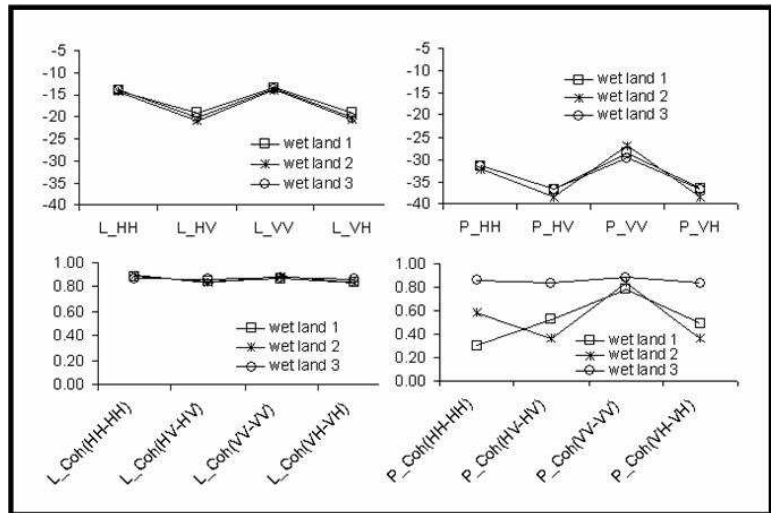


Figure-23: Multi-frequency and Multi-polarized SAR signatures along with InSAR coherence values for three wetland categories.

irrespective of the polarisation state for L band, for the case of P-band, there exists a very high degree of variation amongst the PolInSAR Coherence values of the marked wetland targets. This behaviour of variation in PolInSAR coherence is attributed to differences in the phase centres of different polarisation arising due to oriented volume component for a given wetland target. It can be observed that even for P-band, InSAR coherence at VV polarisation is consistently higher for all the wetland targets as compared to InSAR coherence at HH and VV

polarisation. This is due to the fact that most of the grasses are vertically oriented. Hence even for P-band, the phase centre for VV polarisation is within the grass, where as the phase centre for HH and HV signal is underneath the grasses. The relatively high PolInSAR coherence values for all the three targets at L-band indicates that the volume with which L-band interacts is relatively uniform at all polarisations, where as the variation in P-band PolInSAR coherence clearly indicates that the increased depth of penetration at P-band leads to variation in the phase centres.

6.0 CONCLUSION

This article brings out the salient results of the study carried out to explore and demonstrate potential applications of multi-parametric Radar data in wetland inventory over world famous Keoladeo National Park. Although the results reported in this article utilize multi-parametric SAR data from various satellites and platforms over a span of eight years, the study is just an indicative of exploitation of the Radar data in wetland inventory on operational / routine basis particularly in south Asian countries. It is due to the fact that as on date, in comparison to optical data, the potential of radar data is grossly under investigated and under reported. However, the study clearly suggests that Radar data has a number of unique features that can be exploited in the assessment, monitoring and management of a wetland ecosystem. For example, Radar data can delineate open water habitat and various other wetland habitats, aquatic vegetation with standing water, aquatic vegetation with underlying wet, moist or dry soil. It can delineate different structured vegetation and can also monitor the temporal changes in various wetland habitats. Along with exploring potential of use of Radar data in wetland inventory, authors also explored the possibility of synergistic use of optical and Radar data during cloud free season. It was observed that combined use of radar and optical data provides higher classification accuracies between classes of importance to wetland management. Thus it is strongly advocated to use radar data in conjunction of optical data for achieving better conservation management of wetland ecosystems. Study also indicates that radar data is 3 to 4 fold better in delineating extent of open water habitat, aquatic vegetation categories and the localities of high soil moisture content. For the managers, this information provides vital inputs for planning temporal habitat corridors to manage Eco-tourism, breeding bird habitats and the overall habitat management and monitoring. By means of numerous demonstrative examples reported in this article, authors have demonstrated that Radar data has huge potential to exploit in the field of wetland inventory. In particular, we foresee four major areas that could benefit from the potential applications of Radar data in wetland studies:

- (a) Formulation of models of vegetation succession such as Markov models.
- (b) Explaining and formulating models of inter annual variation in avian guilds and their structure.
- (c) Explaining patterns and process of less known components of aquatic food chain such as the detritus cycles and abundance of macro and micro invertebrates.
- (d) Formulating Habitat Suitability Index (HSI) models for a variety of faunal species including local migrant bird species.

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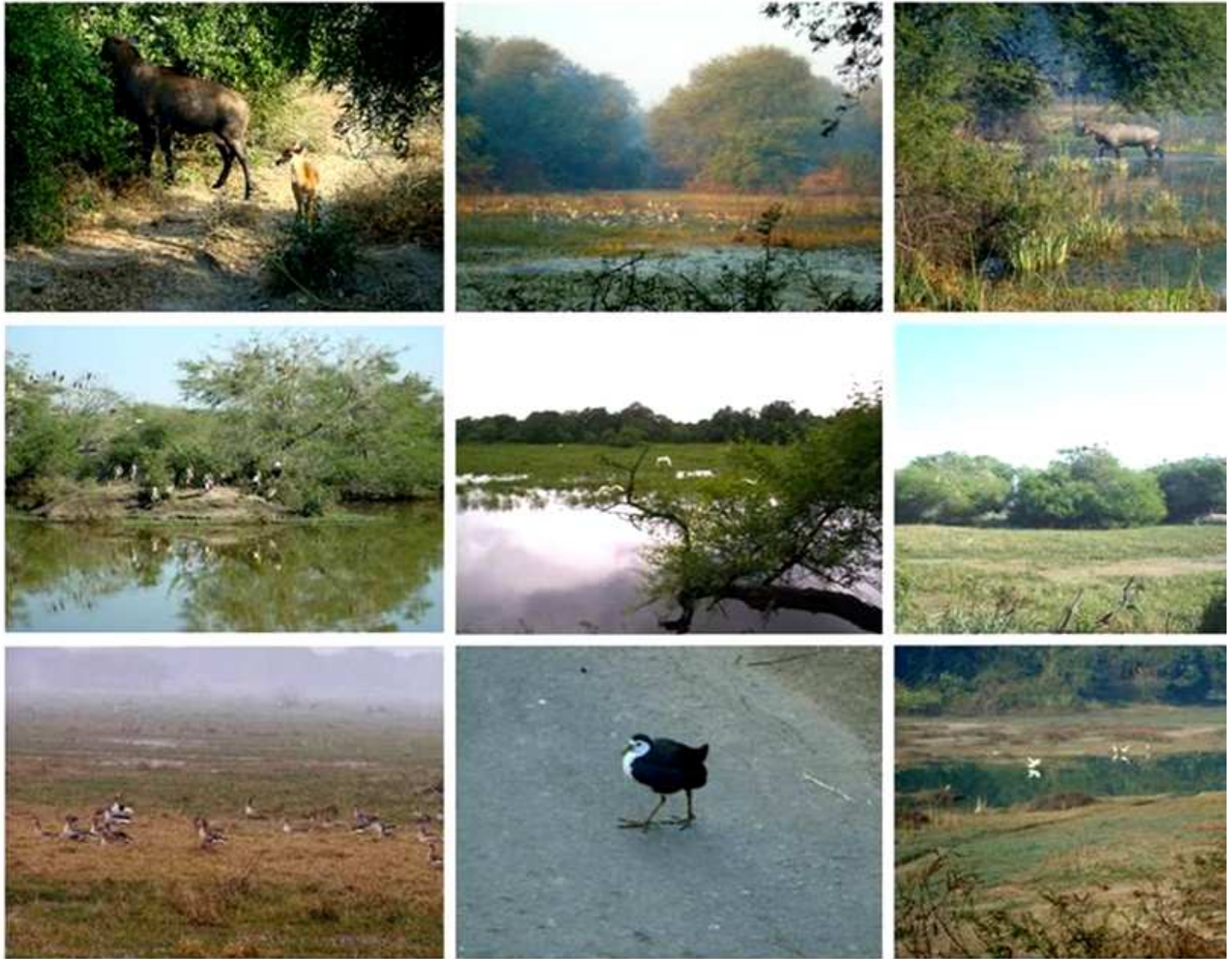
Keoladeo National Park in Different Moods & Colours: Plate1



Keoladeo National Park in Different Moods & Colours: Plate2



Keoladeo National Park in Different Moods & Colours: Plate 3



Keoladeo National Park in Different Moods & Colours: Plate4



Keoladeo National Park in Different Moods & Colours: Plate 5