Journal of Geointerface, Vol. 4, No. 1, July 2025, pp. 125–134 e-ISSN: 2583-6900

Assessing seasonal patterns of Water Hyacinth (*Pontederia crassipes* Mart.) invasion in Samaspur Bird Sanctuary, a Ramsar site using Sentinel-2 data

Ramshida, K.[1,2], Sudhakar Reddy, C. [1,*]

[1] *Forest Biodiversity and Ecology Division, National Remote Sensing Centre, Indian Space Research Organisation, Balanagar, Hyderabad 500 037, Telangana, India*
[2] *Kerala University of Fisheries and Ocean Studies, Kochi, Kerala 682 506, India*

ABSTRACT

Invasive alien plant species are ranked among the most devastating factors threatening global biodiversity. Water hyacinth (*Pontederia crassipes*) is considered one of the most destructive aquatic invasive species. This study leverages Sentinel-2 time series satellite imagery and Random Forest machine learning algorithm to analyze the spatiotemporal dynamics of water hyacinth proliferation in the Samaspur Bird Sanctuary, a designated Ramsar site in India. Monthly land cover analysis from June 2023 to May 2024 revealed seasonal variations, with a maximum cover of 3.48 km^2 during the post monsoon season of October 2023 and a minimum of 2.00 km^2 during the monsoon season of July 2024. Change detection analysis over 2017–2023 continues to reveal a more profound invasion pathway, evidenced by the progressive encroachment on emergent vegetation, terrestrial vegetation, and water bodies. Overlay analysis demonstrated persistent infestations in specific regions, indicating the invasive and resilient nature of water hyacinth. This study not only emphasizes the application of remote sensing in ecological monitoring, but also offers a conceptual framework for prioritizing and implementing specific management interventions to conserve biodiversity in threatened wetlands.

ARTICLE HISTORY

Received: 14 May 2025
Revised: 23 May 2025
Accepted: 26 May 2025

https://doi.org/10.5281/zenodo.15575036

KEYWORDS

Invasion
remote sensing
wetland
change monitoring
Samaspur Bird Sanctuary

1. Introduction

Invasive alien species (IAS) are considered one of the major threats to native biodiversity (Reddy, 2008). Aquatic weeds are capable of flourishing in continuously wet environments and can withstand waterlogged soils for prolonged periods. Water hyacinth, scientifically named *Pontederia crassipes* Mart. (Syn. *Eichhornia crassipes* (Mart.) Solms), belongs to the family Pontederiaceae (POWO, 2025). It is a floating plant native to South America but has been naturalized and invaded in many parts of the world. The plant is regarded as one of the world's 100 worst IAS due to its ability to grow uncontrollably and cause serious ecological problems (Patel, 2012; Degaga, 2018). In the late 1800s, water hyacinth was introduced to India from its native South America as an ornamental plant (Shah, 2018; Dechassa, 2020). Water hyacinth grows best at water temperatures of 28-30°C and at pH levels ranging from 4 to 8 (Shah, 2018). The uncontrolled expansion of water hyacinths leads to the formation of dense mats that block sunlight, reduce oxygen levels, disrupt photosynthesis, obstruct water flow, and compete with native species in aquatic habitats. The disrupted water flow affects both the

*Corresponding author. Email: drsudhakarreddy@gmail.com (SRC), ramshidak2000@gmail.com (RK)

quality and quantity of water, thereby impacting transportation and fishing activities. This reduces the abundance and diversity of the macrophyte community (Mengistu et al., 2017).

Remote sensing provides a valuable tool for mapping and monitoring the distribution of aquatic weeds, enabling their early detection (Schmidt and Witte, 2010). Integrating remote sensing, Geographic Information System (GIS) and machine learning greatly improves invasive species monitoring and management by enabling accurate detection, mapping, and effective control (Reddy et al., 2024). Satellite sensors provide a crucial data source for vegetation mapping and monitoring including applications for wetland and aquatic weeds, with high spatial resolution enabling large scale mapping and species discrimination in a cost effective and time saving manner compared to conventional field work and aerial photography (Schmidt and Witte, 2010). Furthermore, the ability to repeatedly monitor area of interest with temporally dense data sets of high spatial resolution enables the tracking and spatial depiction of the weed infestation as they develop over time (Schmidt and Witte, 2010). A major issue with identifying aquatic weeds from other aquatic plants is that they share similar physical characteristics and grow within or interact with these ecosystems through the mixed or ecological overlap of plant species, which implies that moderate to high spatial and spectral resolutions in the visible and shortwave infrared regions are required (Thamaga and Dube, 2018).

In aquatic ecosystems, remote sensing has successfully contributed in the assessment of the expansion of invasive plant species like the water hyacinth, making it a convenient source of ecological data. Using multispectral remote sensing images, Mukarugwiro et al. (2019) were able to map water hyacinth in Rwandan aquatic ecosystems. The researchers realized that the Random Forest (85%) algorithm was more accurate and reliable than the Support Vector Machine (65%). To be precise, Random Forest performed better in identifying and classifying water hyacinth from other land cover classes. The study affirmed that there are varying levels of water hyacinth invasions in three major Rwandan rivers, and consequently, the infestation is widespread in the lake and other water bodies. Pádua et al. (2022) evaluated spatio-temporal changes in water hyacinth in Lower Mondego, Portugal using high spatial resolution Unmanned Aerial Vehicles (UAV) images, and low-spatial resolution Sentinel-2 Multi Spectral Imager (MSI) images. Their results demonstrate that the Random Forest classifier performs better than other methods including SVM, Gaussian naive bayes, k-nearest neighbors, and artificial neural networks, achieving an overall accuracy of 94%, which showed the efficiency of remote sensing in combating water hyacinth invasion. Thamaga and Dube (2018) highlighted the potential of Sentinel-2 data for assessing the seasonal dynamics and distribution of water hyacinth in the Greater Letaba River system, South Africa. For the Greater Letaba River system, the mapping accuracy obtained was 77.56% using Sentinel-2 data and 68.44% using Landsat-8 data, thus confirming the higher suitability of Sentinel-2. The spectral bands including blue, red, red edge 1, Short Wave Infra Red (SWIR-1), and SWIR-2 are deemed useful in the identification and mapping of the water hyacinth. The development of a spatial decision support system offers a promising pathway to support IAS management (Saranya et al., 2024). Reddy et al. (2025) discussed the advancements in global biodiversity monitoring and the integration of essential variables. This study focuses on monitoring the spatio-temporal distribution of water hyacinth in the Samaspur Bird Sanctuary, by integrating Sentinel-2 imagery with a Random Forest algorithm.

2. Study area

Samaspur wetland is situated in the Rae Bareli district of Uttar Pradesh in India and consists of six lakes, officially recognised as the Samaspur Bird Sanctuary in 1987 (Fig. 1).

It was declared as a Ramsar site because of its significance as the wetland of international importance especially for waterfowl and other aquatic birds. This sanctuary lies between 25° 58' to 26° 01' N latitude and 81° 21'to 81° 25' E longitude and is one of the Important Bird Areas in the country. Private and community land occupies about 370 hectares of the sanctuary's total geographical area of 800 ha. The sanctuary encompasses five interconnected lakes: Samaspur, Mamani, Gorwa Hasanpur, Hakganj, and Rohnia. The sixth lake is called Bissaiya, and it is situated close to the other five lakes, but it is not a part of the main water body; however, it also belongs to the sanctuary. This sanctuary is one of the largest centres for bird migration, especially dur-

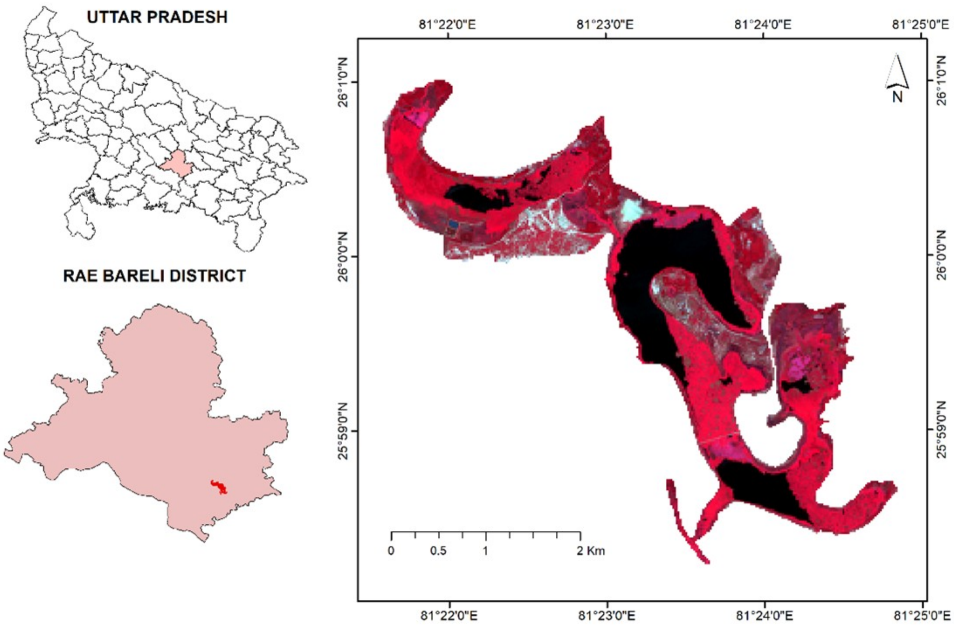

Fig. 1. Location of study area and Sentinel-2 False Colour Composite image (October 2023).

ing the winter season, stretching from November to March, when about 100,000 migratory birds, including species from Siberia and Tibet, flock into the sanctuary in large numbers, making it a popular destination for bird enthusiasts and tourists (Korgaonkar and Gokhale, 2006; Reddy et al., 2009). The region is a part of the Gangetic Plains that has alluvial soil rich in humus, while the surrounding areas feature sandy soil with high saline content. Beyond the sanctuary's boundaries, lake water is utilised for irrigation, hence causing eutrophication due to agricultural runoff. The wetland is perennial, with the depth varying from 0.1 to 5 meters and increasing alkalinity. The area receives an average annual rainfall of approximately 1200 mm, with temperatures varying from 2–3°C to 45°C and humidity around 87% (Kumar and Kanaujia, 2015; Behera et al., 2011). The sanctuary serves as a biodiversity hotspot, hosting 149 species of higher plants, 46 species of fish, over 250 species of resident and migratory birds, and numerous invertebrates, including molluscs and butterflies (Anonymous, 2020). It also houses many terrestrial and aquatic snakes, turtles, frogs, and other higher animals like the blue bull. The local communities heavily depend on the wetlands for activities such as animal grazing, fishing, and groundwater replenishment. One of the main reasons behind the reduced visits of waterfowl to the Samaspur Bird Sanctuary is due to the spread of water hyacinth alongside the water body (Korgaonkar and Gokhale, 2006). The impact of invasion was clearly evident in July 2006, when excessive weed growth caused critically low dissolved oxygen levels in the water, resulting in the death of 200 tons of fish (Korgaonkar and Gokhale, 2006; Reddy et al., 2009).

3. Materials and methods

3.1. Data used

The monitoring of the water hyacinth cover in the specified study area with reference to the land cover is only possible through the periodical study of the land cover patterns in the Samaspur Bird Sanctuary. To examine how far the spatial patterns of water hyacinth differ across the twelve months in the Samaspur Bird Sanctuary, the Sentinel-2 data collected by the Sentinel-2 Multispectral Instrument (MSI) were used. This research concentrated on four of the 13 available spectral bands: B8 (842 nm, VNIR spectrum), B4 (665 nm in the red region), B3 (560 nm in the green region), and B12 (2190 nm in the SWIR region), each providing a spatial resolution of 10/20 meters. SWIR bands significantly enhance spectral separability and accurate classification of water hyacinth using remote sensing because of their high sensitivity to the plant's

Table 1. The areal extent of land cover classes over 12-months period.

Months	Land cover in km^2			
	Aquatic vegetation	Emergent vegetation	Terrestrial vegetation	Water
June	2.15	0.13	4.32	1.73
July	2.00	0.22	4.39	1.71
August	2.57	0.73	3.36	1.68
September	2.87	0.51	3.38	1.57
October	3.48	0.98	1.74	1.78
November	3.46	0.11	3.4	1.37
December	3.27	0.12	3.47	1.47
January	3.15	0.13	3.5	1.56
February	3.04	0.11	3.45	1.74
March	2.84	0.08	3.79	1.63
April	3.09	0.04	3.53	1.68
May	2.67	0.03	4.00	1.63

physio-chemical properties aspects and water content (Thamaga and Dube, 2018). The dataset consists of cloud free images captured in June, July, August, September, October, November, December of 2023, and January, February, March, April, and May of 2024, thereby containing both the dry season and wet season imagery. Additionally, sentinel-2 data from 10 November 2017 was downloaded to compare the changes in the area over a period of time (`https://dataspace.copernicus.eu/`).

3.2. Image classification

The Random Trees classifier in ArcGIS Pro implements Breiman's Random Forest algorithm. The Classification of images was done using the Random Forest (RF) classifier, an advanced technique that can avoid misclassification during the classification of images (Mukarugwiro et al., 2019). This supervised classification algorithm categorizes pixels based on spectral signatures into predefined classes. It minimizes the problem of overfitting through the construction of each tree using a random subset of the training data and features about the majority vote whereby classes are assigned based on the mode of the predicted classes, ensuring the most frequently occurring class represents the final decision. This approach helps minimize individual tree prejudices, addresses large and complicated data, and increases the model's general accuracy (Breiman, 2001; Liaw and Wiener, 2002). The classifier was trained with a minimum of 30 samples per land cover class to enable the classification of satellite data. The training areas for each land cover type were identified using Google Earth, and prior knowledge. The floating vegetation, represented by water hyacinth. Emergent vegetation includes species such as *Typha* and *Ipomoea*. Terrestrial vegetation comprises grasslands, crops, mixed tree cover, and *Prosopis juliflora*. Accuracy assessment is carried out using 100 random points.

3.3. Post classification vegetation analysis

Overlay analysis is a technique in GIS where numerous layers of spatial data are combined in order to determine associations, trends and interaction. A matrix model was used to compare the classified images taken on the two dates - 10 November 2017 and 4 November 2023 to explain the land cover changes due to water hyacinth invasion. This particular approach successfully addresses transitional changes that take place from one land cover class to another at the pixel level.

4. Results and discussion

Land cover classification delineates four distinct land cover types as shown in the Fig. 2. Land cover type changes were observed from a spatiotemporal perspective over a period of one year (June to May). The results (Table 1) show that the water hyacinth increased from a low of 2 km^2 in July to a high of 3.48 km^2 in October due to availability of nutrients after monsoon and stability of water level. The 0.98 km^2 of emergent vegetation was observed in October, while the minimum coverage (0.03 km^2) was recorded in May during the dry season. The spatial extent of the terrestrial vegetation was at its maximum in June (4.32 km^2) due to monsoon and at minimum in October (1.74 km^2) due to inundation. The water extent also remained quite constant throughout the year, with a maximum of 1.78 km^2 in October, showing that the water body is permanent, with only slight variations possible due to seasonal conditions.

The temporal pattern in Fig. 3 clearly indicates that the plant shows a high level of seasonality, and

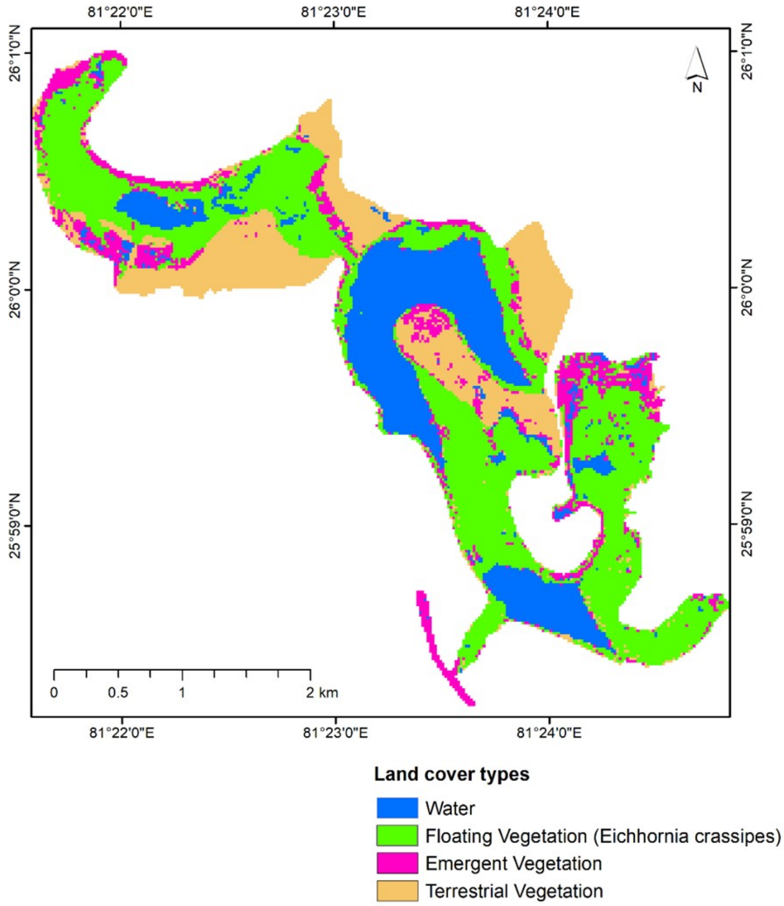

Fig. 2. Land cover map of Samaspur bird sanctuary for October 2023.

the change of coverage is most remarkable during the late monsoon and the post-monsoon season occurring between August and November. The coverage of water hyacinth was lowest in July 2023 where it covered 2 km^2 (5.78% of the total area) and highest in the month of October 2023 at 3.48 km^2 (10.06%) (Table 2). The coverage gradually rose from monsoon period and reached maximum in the post monsoon period (October and November), then fluctuated during the winter season (December to February), where the variation was between 3.04 to 3.27 sq. km. There was a reduction in coverage during the summer months (March to May), with the lowest coverage recorded in May 2024, at 2.67 km^2 (7.72%).

This annual oscillation indicates that water hyacinth growth dynamics are closely directly dependent on environmental conditions including water levels, nutrient availability, and climatic conditions. The overlay analysis demonstrates regions where the species persists continuously from one month to the full year, reflecting sustained and unchanging coverage throughout the analysis period. The total area covered by the species for different durations is summarized in Table 3. Fig. 4 shows that certain areas experienced short-term infestations, with water hyacinth appearing for only 1 to 3 months.

Table 2. The areal extent of *Water hyacinth* over 12-months period.

Month	Area (km^2)	Percentage of area
June	2.15	6.22
July	2.00	5.78
August	2.57	7.43
September	2.87	8.30
October	3.48	10.06
November	3.46	10.00
December	3.27	9.45
January	3.15	9.11
February	3.04	8.79
March	2.84	8.21
April	3.09	8.93
May	2.67	7.72

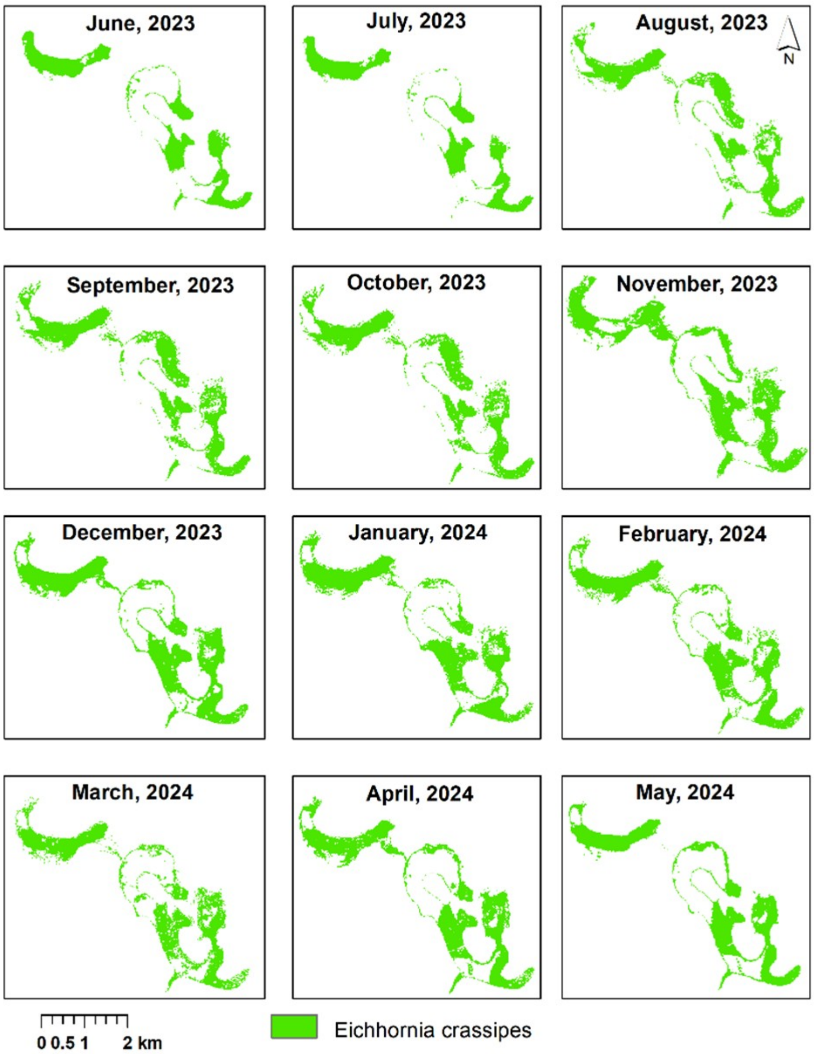

Fig. 3. Monthly varition in the spatial distribution of water hyacinth (June 2023 to May 2024).

Table 3. Frequency of water hyacinth cover and corresponding area (km^2) from June 2023 to May 2024.

No. of months	Area in km^2
1	0.88
2	0.47
3	0.40
4	0.29
5	0.25
6	0.22
7	0.22
8	0.28
9	0.33
10	0.65
11	0.51
12	0.72

The change detection analysis (Fig. 5) over November 2017 to November 2023 revealed significant spread of water hyacinth with the most extent of the spread occurs in the already occupied habitats (Table 4). This invasive species revealed its competence to occupy and saturate aquatic environments by substituting an area of 0.06 km^2 of emergent vegetation and 0.16 km^2 of terrestrial vegetation, invading semi-aquatic and fringe terrestrial areas which have transitioned to aquatic areas. The highest change occurred in open water where an area of 0.82 km^2 was transformed into water hyacinth. Overall classification accuracy obtained is 92%.

Table 4. Change area matrix of land cover (2017–2023).

Land cover	Area (km^2)
Water hyacinth to Water hyacinth (persistent)	2.41
Emergent vegetation to Water hyacinth	0.06
Terrestrial vegetation to Water hyacinth	0.16
Water to Water hyacinth	0.82

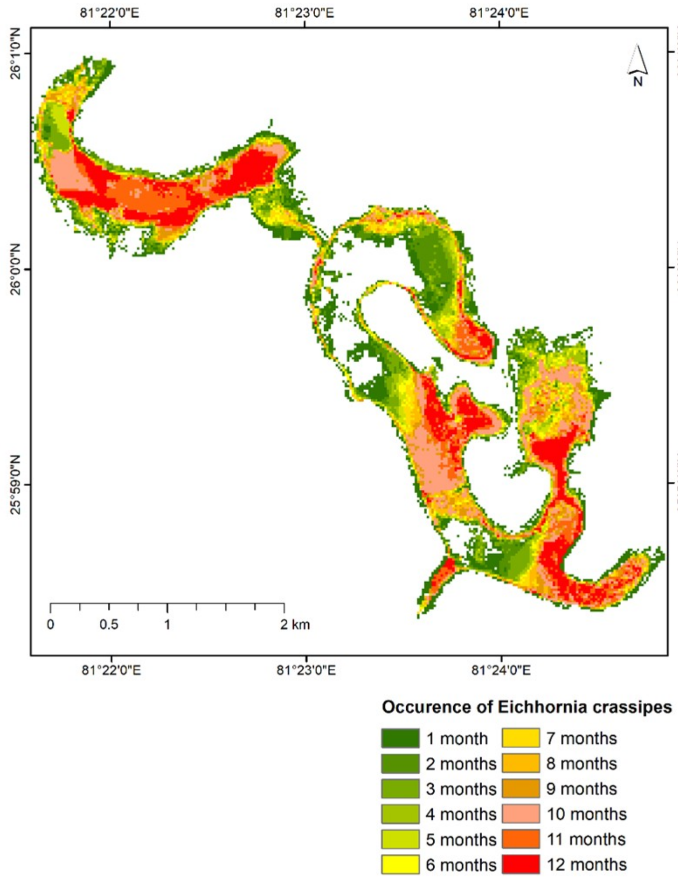

Fig. 4. Spatial overlay analysis shows varying frequency of occurrence for water hyacinth cover (June 2023 to May 2024).

Findings show a clear seasonality in terms of proliferation, with the highest increase noted in the wet season, particularly in the post-monsoon period. During the wet season particularly in post monsoon period, the growth increases to the extent of 10.06 percent in October 2023. The results suggest that the coverage rose from July to October and November 2023, indicating that the growth of the weed is influenced by the rainy season. This period also coincides with high water discharge, high sedimentation rate and high nutrient input into the wetland, which are prerequisites to water hyacinth growth. It was also observed that after the raining period, the rate of growth of water hyacinth reduced from December 2023 to May 2024. The above findings therefore imply that the level of nutrients and the water regime, which are often higher during the rainy season, are perhaps instrumental to the growth of the weed. This period of comparatively slow growth might be credited to reduced nutrient input as well as, water levels (Worqlul et al., 2020). Villamagna and Murphy (2010) pointed out that high concentrations of nutrients in tropic and subtropic areas can accelerate the growth of water hyacinth. Further, this is in support of earlier findings on the impact of nutrient input from runoff water on promoting growth of aquatic macrophytes (Wang and Yan, 2017). There is a clear indication of the level of invasion from the overlay analysis, whereby water hyacinth has a constant coverage of 0.72 km^2 throughout the 12 months.

The ability of the species to survive in the areas for the twelve months is alarming, as it clearly indicates the invasive tendency and highly adaptable nature. This area needs to be addressed urgently for management interventions. The prolonged coverage severely disrupts ecosystem structure and function. These dense vegetative mats block sunlight from penetrating the water column, reducing photosynthetic activity of submerged native plants and disrupting oxygen production. Moreover, as these invasive species die and decompose in large quantities, they consume vast amounts of oxygen during microbial breakdown processes. This results in low dissolved oxygen concentrations, which is detrimental

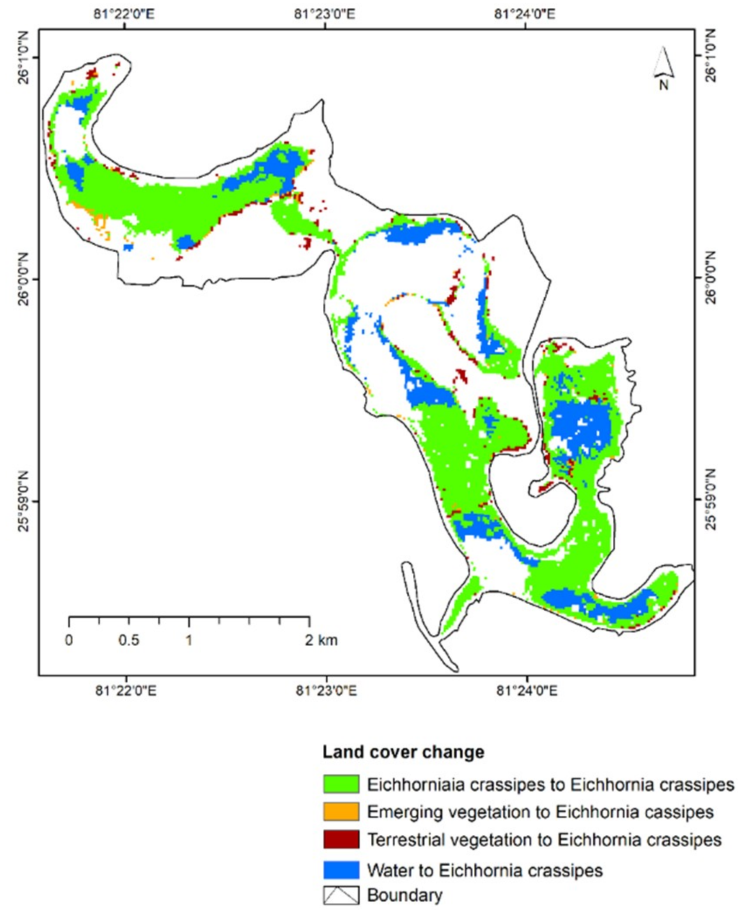

Fig. 5. Change detection of land cover to water hyacinth (2017–2023).

to aquatic fauna, and may lead to collapse of the aquatic food web. The species affects the stream's hydrological regime by limiting water access and interrupting continuity for aquatic inhabitants and consequently, degrading the habitat's quality. This will cause reduction in water quality through oxygen depletion, increased water turbidity and eutrophication besides worsening of hydrological cycle by high rate of evapotranspiration, water blockage through formation of dense mats, which hampers on navigation, irrigation, and fish farming as well as contributing to huge losses on dependent communities (Patel, 2012; Dersseh et al., 2019).

Analysing the changes of water hyacinth with respect to the spatiotemporal dimension of land cover is important for understanding ecosystem decline as a result of the proliferation of invasive aquatic weed. The result suggests that there are alterations in the land cover classes especially the increase of water hyacinth, over a period of six years (2017–2023). Replacement of 0.06 km^2 of emergent vegetation and 0.16 km^2 of terrestrial vegetation reveal extent of competitiveness by this invasive weed. The largest conversion was observed in open water habitats where 0.82 km^2 was changed into water hyacinth, which is a considerable change at an ecosystems level. This sanctuary, which is one of the major hubs for migratory birds, may experience both direct and indirect effect of water hyacinth. Moderate growth improves habitats for aquatic prey, thus favouring some bird species; however, excessive growth is detrimental to waterbirds since it hinders access to food sources, depletes oxygen, and limiting surface water availability (Villamagna and Murphy, 2010).

Khan's (2010) research showed that bird species richness was significantly reduced in 2009 during the highest water hyacinth coverage, which hindered the formation of suitable habitats and affected the population of bird species. Water hyacinth can be turned into a resource through community-led management. Practical uses include compost, biogas, handicrafts, paper, and wastewater treatment. Local communities can help control its spread through manual removal, biological control and regular monitoring. Promoting water hyacinth-based livelihoods and raising awareness strengthens community engagement (Abba and Sabarinath, 2025). An Earth observation-based approach provides a scientifically robust framework for the assessment, modelling, and management of biological invasions, enabling spatially explicit monitoring, early detection, and informed decision-making for effective control strategies (Reddy and Saranya, 2023).

5. Conclusions

Focusing on the Samaspur wetlands, this study underlines the important ecological issues posed by water hyacinth in terms of the seasonal proliferation. The invasive species outcompetes native vegetation and alters hydrological regimes, posing a threat to the sanctuary's ecological integrity and its role as a breeding and stopover site for migratory birds. Efficient management strategies are essential to prevent its spread and maintain the functionality of wetland ecosystems. Future research should focus on integrating multi-source data, including hyperspectral imagery and UAV-based observations, to improve species differentiation and mapping precision. Additionally, developing automated, real-time monitoring systems coupled with predictive modelling can enhance early warning and risk assessment.

Acknowledgements

Authors are thankful to Director, NRSC for suggestions and encouragement.

CRediT statement

CSR: Conceptualization, Supervision, Methodology, Resources, Writing – review & editing. **RK**: Formal analysis, Methodology, Software, Visualization. Writing – original draft.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

Abba, A., Sabarinath, S., 2025. Sustainable management of water hyacinth (*Eichhornia crassipes*): Community-led strategies for livelihood enhancement in rural India. *Results in Engineering* 105033.

Anonymous, 2020. Addition of ten new Ramsar sites in India - a 2020 beginning. Sarovar Saurabh, ENVIS newsletter. *SACON, Tamil Nadu* 16(3), 4–10.

Behera, M.D., Chitale, V.S., Shaw, A., Roy, P.S., Murthy, M.S.R., 2011. Wetland Monitoring, serving as an index of Land Use Change-A study in Samaspur Wetlands, Uttar Pradesh, India. *Journal of the Indian Society of Remote Sensing* 40(2), 287–297. https://doi.org/10.1007/s12524-011-0139-6.

Breiman, L., 2001. Random forests. *Machine learning* 45, 5–32. URL: https://link.springer.com/article/10.1023/A:1010933404324.

Dechassa, N., 2020. Origin, distribution, impact and management of water hyacinth (*Eichhornia crassipes* (Martius) Solm): ArReview. *Dechassa, Journal of Environment and Earth Science* 10(10), 13–18. https://doi.org/10.7176/JEES/10-10-02.

Degaga, A.H., 2018. Water hyacinth (*Eichhornia crassipes*) biology and its impacts on ecosystem, biodiversity, economy and human well-being. *Journal of Life Science and Biomedicine* 8(6), 94–100.

Dersseh, M.G., Melesse, A.M., Tilahun, S.A., Abate, M., Dagnew, D.C., 2019. Water hyacinth: review of its impacts on hydrology and ecosystem services—Lessons for management of Lake Tana, in: Elsevier eBooks, p. 237–251. https://doi.org/10.1016/b978-0-12-815998-9.00019-1.

Khan, T.N., 2010. Temporal changes to the abundance and community structure of migratory waterbirds in Santragachi Lake, West Bengal, and their relationship with water hyacinth cover. *Current Science* 99, 1570–1577.

Korgaonkar, C., Gokhale, Y., 2006. Stakeholder Analysis for Conservation and Management of Samaspur Bird Sanctuary, Uttar Pradesh. TERI Report. URL: https://wgbis.ces.iisc.ac.in/energy/lake2006/programme/programme/proceedings/fullpaper_pdfs/Yogesh251106.pdf.

Kumar, A., Kanaujia, A., 2015. Waterbird diversity of Samaspur Bird Sanctuary, Rae Bareli District, Uttar Pradesh. *Discovery Nature* 9(23), 48–57.

Liaw, A., Wiener, M., 2002. Classification and regression by Random Forest. *R News* 2, 18–22. URL: https://journal.r-project.org/articles/RN-2002-022/RN-2002-022.pdf.

Mengistu, B.B., Unbushe, D., Abebe, E., 2017. Invasion of water hyacinth (*Eichhornia crassipes*) is associated with decline in macrophyte biodiversity in an Ethiopian Rift valley lake - Abaya. *Open Journal of Ecology* 07(13), 667–681. https://doi.org/10.4236/oje.2017.713046.

Mukarugwiro, J.A., Newete, S.W., Adam, E., Nsanganwimana, F., Abutaleb, K.A., Byrne, M.J., 2019. Mapping distribution of water hyacinth (*Eichhornia crassipes*) in Rwanda using multispectral remote sensing imagery. *African Journal of Aquatic Science* 44(4), 339–348. https://doi.org/10.2989/16085914.2019.1650712.

Patel, S., 2012. Threats, management and envisaged utilizations of aquatic weed *Eichhornia crassipes*: an overview.

Reviews in Environmental Science and BioTechnology 11(3), 249–259. https://doi.org/10.1007/s11157-012-9289-4.

POWO, 2025. *Plants of the World Online*. Facilitated by the Royal Botanic Gardens, Kew. URL: https://powo.science.kew.org/. retrieved 23 May 2025.

Pádua, L., Antão-Geraldes, A.M., Sousa, J.J., Rodrigues, M.Â., Oliveira, V., Santos, D., Miguens, M.F.P., Castro, J.P., 2022. Water Hyacinth (*Eichhornia crassipes*) detection using coarse and high resolution multispectral data. *Drones* 6(2), 47. https://doi.org/10.3390/drones6020047.

Reddy, C.S., 2008. Catalogue of invasive alien flora of India. *Life Science Journal* 5(2), 84–89.

Reddy, C.S., Athira, K., Mudalkar, S., 2025. Evolution of global biodiversity monitoring: Innovations, modern approaches and integration with essential variables. *Journal of the Indian Society of Remote Sensing* https://doi.org/10.1007/s12524-025-02211-1.

Reddy, C.S., Ramshida, K., Kumari, J., Shijila, P.S., Gulzar, R., Khuroo, A.A., 2024. Modelling the global and regional niches of major invasive alien plant species of India, in: *Asian Conference on Remote Sensing (ACRS 2024)*, Sri Lanka. pp. 1–17,.

Reddy, C.S., Rangaswamy, M., Pattanaik, C., Jha, C.S., 2009. Invasion of alien species in wetlands of Samaspur bird sanctuary, Uttar Pradesh, India. *Asian Journal of Water, Environment and Pollution* 6(3), 43–50.

Reddy, C.S., Saranya, K.R.L., 2023. Earth Observation-based approach for assessment, modelling and management of biological invasions – scope and future, in: *Proceedings of a National Conference - Bioinvasions, Trends, Threats and Management*, Kerala State Biodiversity Board, Thiruvananthapuram. p. 147–157. ISBN: 78-93-6039-641-1.

Saranya, K.R.L., Satish, K.V., Reddy, C.S., 2024. Remote sensing enabled essential biodiversity variables for invasive alien species management: towards the development of spatial decision support system. *Biological Invasions* 26, 943–951. https://doi.org/10.1007/s10530-023-03240-y.

Schmidt, M., Witte, C., 2010. Monitoring aquatic weeds in a river system using SPOT 5 satellite imagery. *Journal of Applied Remote Sensing* 4(1), 043528. https://doi.org/10.1117/1.3431039.

Shah, N.C., 2018. *Eichhornia crassipes* (Pontederiaceae): an exotic aquatic menace in India and its possible uses. *Journal of Economic and Taxonomic Botany* 42, 1–4.

Thamaga, K.H., Dube, T., 2018. Remote sensing of invasive water hyacinth (*Eichhornia crassipes*): A review on applications and challenges. *Remote Sensing Applications: Society and Environment* 10, 36–46. https://doi.org/10.1016/j.rsase.2018.02.005.

Villamagna, A.M., Murphy, B.R., 2010. Ecological and socioeconomic impacts of invasive water hyacinth (*Eichhornia crassipes*): A review. *Freshwater Biology* 55, 282–298. https://doi.org/10.1111/j.1365-2427.2009.02294.x.

Wang, Z., Yan, S.H., 2017. Impact of water hyacinth on aquatic environment in phytoremediation of eutrophic lakes, in: *Water Hyacinth: Environmental Challenges, Management and Utilization*. China, pp. , 204–249.

Worqlul, A.W., Ayana, E.K., Dile, Y.T., Moges, M.A., Dersseh, M.G., Tegegne, G., Kibret, S., 2020. Spatiotemporal dynamics and environmental controlling factors of the Lake Tana water hyacinth in Ethiopia. *Remote Sensing* 12(17), 1–21. https://doi.org/10.3390/rs12172706.

