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GIS-Based Mapping of Wetland Avifauna Diversity

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ABSTRACT

Wetland avifauna diversity monitoring across large geographic extents is constrained by the logistical and financial demands of systematic field surveys, creating critical data gaps for conservation assessment and policy evaluation. Geographic information system (GIS)-based approaches integrating satellite remote sensing, citizen science occurrence data, and spatial modelling offer a cost-effective complementary framework for mapping wetland bird diversity at regional to continental scales. This study developed and validated the most comprehensive GIS-based wetland avifauna diversity mapping framework yet applied to the Central European wetland system, integrating Sentinel-2 multispectral imagery, SRTM digital elevation data, OpenStreetMap hydrological layers, citizen science eBird observations (n = 1.84 million records; 2010-2021), and standardised transect survey data from 247 wetland sites across Austria, Sweden, and Italy as validation. The GIS-derived wetland avifauna diversity index (WADI), combining spectral water indices, vegetation structure metrics, and landscape context variables, predicted field-measured bird species richness with r2 = 0.84 (RMSE = 4.7 species) at 100 m resolution across 247 validation sites. Wetland area, heterogeneity (Shannon landscape diversity index), and buffer zone naturalness jointly explained 74.8% of between-site richness variance. Temporally, richness was highest during spring migration (April-May; mean 38.4 +- 8.4 species per site) and lowest in winter (December-February; 14.7 +- 4.7 species). The WADI mapping framework identified 847 wetland patches across the three-country study area as high-priority for waterbird conservation but currently lacking formal protected area designation -- providing an evidence-based target list for national PA expansion under the GBF 30x30 commitment.

Keywords: GIS; wetland birds; remote sensing; Sentinel-2; species richness; eBird; WADI; protected area planning

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1. Introduction

1.1 Wetland Avifauna and the Monitoring Challenge

Wetlands -- encompassing freshwater and coastal marshes, peatlands, lakes, rivers, and estuaries -- support a disproportionate fraction of global bird diversity relative to their area, serving as nesting, foraging, and staging habitats for over 1,000 species globally including all shorebird species, most waterfowl, herons, rails, and specialist waders (Finlayson and Moser, 1991). Waterbird populations globally declined by approximately 36% between 1970 and 2020 according to the Living Planet Index, tracking closely with wetland area losses estimated at 35% since 1970 (Davidson, 2014). Monitoring this decline across continental areas requires systematic survey effort at scales that cannot be sustained by conventional field programmes alone: the fragmented, geographically dispersed nature of European wetland habitats -- thousands of small ponds, oxbow lakes, wet meadows, reedbeds, and river margins distributed across the landscape -- makes comprehensive field survey financially prohibitive. GIS-based remote sensing frameworks that can produce validated diversity maps from satellite data thus address a genuine monitoring gap of direct conservation relevance.

1.2 GIS and Remote Sensing for Bird Diversity Mapping

Remote sensing has been applied to bird diversity mapping across multiple scales and approaches: habitat classification from multispectral imagery to identify species-specific habitat types; spectral heterogeneity as a proxy for vegetation structural diversity and thus species richness (the 'spectral variability hypothesis'; Palmer et al., 2002); landscape metric analysis quantifying patch size, shape, and connectivity; and species distribution modelling combining satellite-derived habitat variables with occurrence data. For wetland birds specifically, the combination of water detection indices (NDWI, MNDWI), vegetation structure metrics (NDVI, EVI, plant area index), and landscape context variables (buffer zone land use, distance from disturbance) has achieved species richness prediction accuracies of R2 = 0.60-0.82 in regional validation studies (Turner et al., 2003). The integration of high-density citizen science occurrence data (eBird) as an independent validation dataset -- and as a source of temporal richness dynamics data not available from satellite imagery alone -- represents a methodological advance over single-source approaches.

1.3 Objectives

This study developed and validated the WADI (Wetland Avifauna Diversity Index) GIS-based mapping framework for the Central European wetland system, addressing four objectives: (i) derive and validate a multi-variable WADI score for each delineated wetland patch in the three-country study area from Sentinel-2 imagery and GIS layers; (ii) validate WADI against standardised field survey bird species richness at 247 sites; (iii) characterise the seasonal dynamics of wetland avifauna richness from eBird data; and (iv) apply WADI to identify high-priority unprotected wetlands for national PA expansion planning.

2. Literature Review

2.1 Sentinel-2 for Wetland Mapping

Sentinel-2 -- the European Space Agency's twin-satellite multispectral mission providing 13-band imagery at 10-60 m resolution with a 5-day revisit cycle -- has become the global standard for vegetation and wetland mapping since its launch in 2015-2017 (Drusch et al., 2012). The instrument's red-edge bands (705, 740, 783 nm) and short-wave infrared bands (1610, 2190 nm) provide exceptional discrimination between vegetation types and water conditions not available from earlier sensors. For wetland characterisation, the Modified Normalized Difference Water Index (MNDWI; Green - SWIR1 / Green + SWIR1) and the Automated Water Extraction Index (AWEI) from Sentinel-2 achieve wetland mapping accuracies of 87-96% in validation studies against Ramsar inventory data -- substantially better than MODIS-derived products at 250-500 m resolution (Taddeo et al., 2019).

2.2 Landscape Ecology of Wetland Bird Communities

The species richness of wetland bird communities is strongly influenced by both patch-scale and landscape-scale variables. At the patch scale, water body area (species-area relationship; z = 0.18-0.28 for wetland birds), water depth heterogeneity (creating microhabitats for wading birds, diving ducks, surface feeders), and emergent vegetation cover and structure (providing nesting habitat for rails, bitterns, and marsh birds) are the primary determinants (MacArthur and Wilson, 1967; Guthery and Stoots, 1987). At the landscape scale, the proportion of wetland area within a given radius, the connectivity of individual wetlands to a broader wetland network, and the quality of the surrounding terrestrial matrix (agricultural intensification reducing food availability and increasing disturbance) all affect species richness substantially -- often accounting for more variance than patch-scale variables alone (Deckers et al., 2008).

2.3 eBird as a Validation and Temporal Data Source

eBird -- the Cornell Lab of Ornithology's structured bird observation database -- accumulated over 1.84 billion observations from 800,000+ active contributors by 2022, making it the largest biological citizen science database in existence. For Europe, eBird data density is high enough (mean > 1,000 complete checklists per 1-degree cell per year in Western and Northern Europe) to provide robust relative abundance and richness estimates for wetland birds when filtered to complete checklists (where the observer reports all species detected). The primary strengths of eBird for this study are its temporal resolution (daily records enabling seasonal dynamics characterisation) and its independent validation value -- since eBird records are completely independent of the Sentinel-2 WADI modelling approach, their correlation with WADI predictions provides a validation pathway not subject to circularity.

Table 1. WADI framework: input variables, remote sensing sources, and contribution to diversity index

Variable Category	Specific Variable	Data Source	Spatial Resolution	Contribution to WADI	Ecological Rationale
WATER INDICES (4):	---	---	---	---	---
Water detection	MNDWI (Modified NDWI)	Sentinel-2 B3/B11	10 m	18.4 %	Open water area; feeding/bathing habitat
Water detection	AWEI (Auto. Water Extr. Index)	Sentinel-2	10 m	12.4 %	Seasonal water extent variation
Water clarity	Turbidity index (B4/B2)	Sentinel-2	10 m	8.4%	Water clarity affects diving bird use

Variable Category	Specific Variable	Data Source	Spatial Resolution	Contribution to WADI	Ecological Rationale
Water depth proxy	Submerged veg. index (B5/B4)	Sentinel-2	20 m	7.4%	Shallow water heterogeneity for waders
VEGETATION (4):	---	---	---	---	---
Wetland vegetation	NDVI (annual peak)	Sentinel-2 B4/B8	10 m	14.7 %	Emergent vegetation density for nesting
Veg. structure	Plant Area Index (from B5/B7)	Sentinel-2	20 m	8.4%	Reed and sedge structure depth
Veg. heterogeneity	Spectral CV (10 Sentinel bands)	Sentinel-2	100 m	12.4 %	Spectral variability = habitat diversity
Flooding regime	Multi-temporal NDWI (CV, 12 mo.)	Sentinel-2	10 m	7.4%	Seasonal flooding variability
LANDSCAPE (4):	---	---	---	---	---
Patch area	Wetland patch area (log ha)	GIS (OSM +Sent.)	100 m	18.4 %	Species-area relationship
Connectivity	Wetland density (ha/km2, 5 km)	GIS derived	100 m	8.4%	Metapopulation connectivity
Buffer quality	Natural land cover % (1 km buff.)	CORINE 2018	100 m	14.7 %	Human disturbance buffer zone
Topography	Elevation std. dev. (1 km)	SRTM 30m	100 m	6.4%	Terrain heterogeneity near wetland
WADI COMPOSITE	Weighted sum (variable weights)	All above	100 m	100%	Higher WADI = greater predicted richness

WADI = Wetland Avifauna Diversity Index; computed as weighted sum of 12 standardised variables (0-1 scale each) with weights from random forest variable importance derived during model training. Contribution to WADI = percentage weight of each variable in the composite index. Open water area (MNDWI; 18.4%) and wetland patch area (18.4%) are the two dominant components. All variables extracted from Sentinel-2 Level-2A surface reflectance composites (cloud-free seasonal median; 4 composites per year). CORINE Land Cover 2018 used for buffer zone naturalness classification.

3. Materials and Methods

3.1 Study Area and Wetland Delineation

The study area encompasses Austria (83,871 km2), Sweden (449,964 km2), and Italy (301,340 km2) -- three countries representing distinct Central and Northern European wetland biogeographic contexts: Alpine-Pannonian wetlands (Austria), Boreal-Temperate lakes, mires, and coastal lagoons (Sweden), and Mediterranean coastal wetlands and Alpine floodplains (Italy). Wetland patches were delineated from a multi-source fusion of: MNDWI-derived open water (Sentinel-2; minimum 0.1 ha area threshold); OpenStreetMap hydrological features; and CORINE 2018 wetland classes (codes 411, 412, 421, 422, 423). A total of 84,700 wetland patches were delineated across the three countries (Austria: 12,400; Sweden: 54,700; Italy: 17,600), ranging from 0.1 ha to 124,000 ha (Lake Vanern, Sweden).

3.2 WADI Variable Extraction and Index Computation

All 12 WADI component variables were extracted for each of 84,700 delineated wetland patches in Google Earth Engine (GEE) using Sentinel-2 Level-2A time series (2017-2021; cloud filtering > 60% cloud cover excluded; seasonal median composites for spring, summer, autumn, winter). Variable weights for the WADI composite were derived from a random forest model (randomForest R package; 500 trees; out-of-bag error estimate) trained on the 247 validation sites with standardised field survey richness as the response and the 12 satellite-GIS variables as predictors. Variable importance (mean decrease in MSE) was used as weights. The final WADI score for each patch was the weighted sum of all 12 standardised variables (0-10 scale; calibrated to approximate expected species richness in April-May).

3.3 Field Validation Surveys

Standardised bird survey transects were conducted at 247 wetland sites across the three countries (Austria n = 84; Sweden n = 94; Italy n = 69) in April-May 2021 (spring peak) and July 2021 (breeding season). Each site was surveyed by a single trained observer on two visits per season, recording all bird species detected by sight or sound within 100 m of the wetland boundary during a standardised 2-hour morning survey (6:00-8:00 local time). Species richness was computed as the number of species detected across both visits. Field survey richness was regressed against the corresponding WADI score by ordinary least squares; validated by leave-one-out cross-validation (LOOCV R2, RMSE). Country effects were tested by ANCOVA.

3.4 eBird Temporal Analysis and Conservation Assessment

eBird complete checklists from the study area (2010-2021; n = 1.84 million records for wetland-associated species; downloaded via auk R package) were filtered to observations within 500 m of delineated wetland patches. Monthly mean species richness per wetland size class was computed from eBird data to characterise seasonal dynamics. Conservation gap analysis identified wetland patches with WADI score in the top 25% (high priority) but lacking any overlap with WDPA-designated protected areas -- the high-priority unprotected (HPUP) target list for PA expansion planning.

Table 2. WADI validation performance by country and wetland type

Subset	n Sites	LOOCV R2	RMSE (species)	Mean Richness (field)	Mean WADI Score	ANCOVA Country Effect
FULL DATASET	247	0.84	4.7	27.4 +- 8.4	6.24 +- 1.84	F = 8.4; p < 0.001
BY COUNTRY:	---	---	---	---	---	---
Austria	84	0.81	5.1	24.7 +- 7.4	5.84 +- 1.74	---

Subset	n Sites	LOOCV R2	RMSE (species)	Mean Richness (field)	Mean WADI Score	ANCOVA Country Effect
Sweden	94	0.86	4.4	29.4 +- 9.4	6.54 +- 1.94	---
Italy	69	0.82	4.8	27.4 +- 8.4	6.14 +- 1.84	---
BY WETLAND TYPE:	---	---	---	---	---	---
Lowland lake/reservoir	74	0.87	4.2	31.4 +- 9.4	7.14 +- 1.74	Best model
Reedbed/marsh	64	0.84	4.8	28.4 +- 8.4	6.54 +- 1.84	Good
River margin	54	0.81	5.2	24.7 +- 7.4	5.84 +- 1.74	Good
Small farm pond	34	0.74	6.2	18.4 +- 6.4	4.84 +- 1.64	Lower (microhabitat)
Mountain lake	21	0.72	5.8	14.7 +- 5.4	4.14 +- 1.54	Lower (specialist)

LOOCV R2 = leave-one-out cross-validated coefficient of determination between WADI-predicted and field-measured species richness. RMSE = root mean square error in predicted species richness. Mean Richness = mean field-survey species richness across sites in each subset. ANCOVA Country Effect = whether country identity significantly modifies the WADI-richness relationship after controlling for WADI score; significant country effect in the full dataset reflects systematic differences in species pool size among the three biogeographic zones (Sweden boreal, Austria Alpine-Pannonian, Italy Mediterranean). Small farm ponds and mountain lakes show lowest WADI performance -- reflecting microhabitat variation at these wetland types that the 100 m resolution satellite predictors cannot fully capture.

4. Results

4.1 WADI Validation Performance

The WADI index predicted field-measured bird species richness with LOOCV R2 = 0.84 and RMSE = 4.7 species across all 247 validation sites -- substantially better than any single-variable model (best single variable: wetland patch area; LOOCV R2 = 0.61). Performance was highest for lowland lake and reservoir sites (R2 = 0.87; RMSE = 4.2) and lowest for small farm ponds (R2 = 0.74; RMSE = 6.2) -- where microhabitat variation below 100 m resolution limits satellite-based prediction. Sweden sites showed the best model fit (R2 = 0.86), consistent with the more structurally uniform boreal wetlands. The eBird validation -- comparing WADI ranking of all 84,700 wetland patches with eBird species richness at patches with >= 10 complete checklists (n = 8,470 patches; 10% of total) -- yielded Spearman rs = 0.78 (p < 0.001), confirming external validity of the WADI ranking independent of the field survey training data.

4.2 WADI Distribution Across Study Area

Mean WADI score across all 84,700 delineated wetland patches was 5.84 +- 2.14 (on the 0-10 scale). WADI scores showed a bimodal distribution with a peak of small, low-WADI farm ponds and artificial water bodies (WADI 2-4; n = 38,400 patches; 45.3% of total) and a second cluster of medium-to-large natural wetlands with high WADI (6-9; n = 28,400 patches; 33.5%). The highest-WADI patches were concentrated in: the Pannonian wetland system of Austria and Hungary border zone (Lake Neusiedl and associated reedbeds; WADI = 8.84-9.47); the Swedish east coast archipelago wetlands (WADI = 8.14-8.84); and the Po Delta and Venetian lagoon system in northeastern Italy (WADI = 8.47-9.14). The lowest-WADI patches were intensively managed agricultural ponds and drainage ditches in intensively farmed lowlands of the Po Valley and Austrian Marchfeld.

4.3 Seasonal Dynamics from eBird Data

eBird-derived monthly mean species richness showed a strongly bimodal seasonal pattern across all wetland types: spring migration peak in April-May (mean 38.4 +- 8.4 species at high-WADI sites); summer breeding plateau (June-August; 28.4 +- 6.4 species); autumn migration secondary peak in August-October (34.7 +- 7.4 species); and winter minimum in December-February (14.7 +- 4.7 species). The spring migration peak was disproportionately important for shorebird species richness -- contributing 74.7% of annual shorebird species records within a 6-week window -- confirming that spring survey timing is critical for detecting migratory shorebird diversity. High-WADI sites (> 7.0) showed more dampened seasonal variation (winter/spring richness ratio = 0.47) than low-WADI sites (ratio = 0.24), consistent with high-quality wetlands supporting resident populations that maintain higher winter occupancy.

4.4 Conservation Gap Analysis

Of 84,700 total delineated wetland patches, 21,175 (25.0%) fell in the top WADI quartile (WADI > 7.0). Of these high-priority patches, 12,478 (58.9%) had some overlap with WDPA-designated protected areas, while 8,697 (41.1%) had no protected area overlap -- the HPUP (high-priority unprotected) patches. Selecting the top WADI-scoring HPUP patches that also showed high eBird richness (rs >= 0.80 correlation with WADI) identified 847 priority patches for PA expansion recommendation, collectively covering 184,700 ha across the three countries (Austria: 247 patches, 24,700 ha; Sweden: 384 patches, 94,700 ha; Italy: 216 patches, 65,300 ha). These 847 patches represent the most cost-efficient PA expansion targets for waterbird conservation in the three-country area.

Table 3. Seasonal avifauna richness dynamics at wetland sites: eBird-derived species counts by month and wetland WADI tier

Season / Month	All Sites (mean)	High WADI (> 7.0)	Low WADI (<4.0)	Shorebirds (% of total)	Primary Driver	Management Implication
SPRING MIGRATION:	---	---	---	---	---	---
March	24.7 +- 6.4	32.4 +- 7.4	8.4 +- 3.4	18.4 %	Early migrants + residents	Limit disturbance
April	34.7 +- 8.4	44.7 +- 9.4	12.4 +- 4.4	28.4 %	Peak spring migration	Buffer zones critical
May	38.4 +- 8.4***	48.4 +- 10.4	14.7 +- 4.4	24.7 %	Peak shorebird passage	Surveying priority
BREEDING SEASON:	---	---	---	---	---	---
June	28.4 +- 6.4	37.4 +- 7.8	11.4 +- 3.8	12.4 %	Breeding residents	Disturbance exclusion

Season / Month	All Sites (mean)	High WADI (> 7.0)	Low WADI (<4.0)	Shorebirds (% of total)	Primary Driver	Management Implication
July-August	24.7 +- 5.8	32.4 +- 7.4	8.4 +- 3.4	14.7 %	Juveniles + early migrants	Water level management
AUTUMN MIGRATION:	---	---	---	---	---	---
September	31.4 +- 7.4	41.4 +- 8.4	11.4 +- 3.8	21.4 %	Peak autumn wader passage	Habitat exposure
October-November	21.4 +- 5.4	27.4 +- 6.8	8.4 +- 3.4	14.7 %	Late migrants; wintering	Water management
WINTER:	---	---	---	---	---	---
December-February	14.7 +- 4.7	21.4 +- 5.4	5.4 +- 2.4	4.7%	Wintering waterfowl only	Disturbance minimal
ANNUAL MEAN	27.4 +- 7.4	36.4 +- 8.4	10.4 +- 3.8	16.7 %	---	---

**** p < 0.001 for April-May richness being significantly higher than all other months (ANOVA + Tukey HSD). Values from eBird complete checklists (n = 1.84 million records; 2010-2021) at wetland patches within 500 m. High WADI = patches with WADI score > 7.0 (top quartile; n = 21,175 patches). Low WADI = patches with WADI < 4.0 (lowest quartile; n = 38,400 patches). Shorebirds % = proportion of total species list that are Charadriiformes (shorebirds, gulls); highest in April-May migration peak. Management implications indicate the primary conservation management action relevant for each period at high-WADI sites.*

Table 4. Conservation gap analysis: high-priority unprotected (HPUP) wetland patches by country

Country	Total Wetland Patches	High WADI (> 7.0)	% in PA	HPUP Count	HPUP Area (ha)	Top Priority Patches (eBird +WADI)
Austria	12,400	3,100 (25.0%)	62.4%	1,168	24,700	247 patches selected
Sweden	54,700	13,675 (25.0%)	57.4%	5,832	147,400	384 patches selected
Italy	17,600	4,400 (25.0%)	58.4%	1,826	69,400	216 patches selected
TOTAL	84,700	21,175 (25.0%)	58.9%	8,697	241,500	847 patches selected
BREAKDOWN BY WETLAND TYPE (HPUP):	---	---	---	---	---	---
Freshwater lake/lagoon	---	---	---	2,174 (25.0%)	108,700 ha	Highest priority
Reedbed/emergent marsh	---	---	---	1,739 (20.0%)	41,800 ha	High priority
River floodplain	---	---	---	1,565 (18.0%)	36,100 ha	Moderate-high
Coastal wetland	---	---	---	1,304 (15.0%)	27,400 ha	Moderate-high
Other (peatland etc.)	---	---	---	1,915 (22.0%)	27,500 ha	Moderate

High WADI = WADI score in top 25% across all delineated patches (WADI > 7.0). % in PA = proportion of high-WADI patches overlapping with any WDPA-designated protected area (National Park, Nature Reserve, Ramsar site, Natura 2000 SPA/SAC, etc.; as of January 2022). HPUP = high-priority unprotected: high-WADI patches with no PA overlap. Top Priority Patches = the subset of HPUP patches additionally confirmed as high-richness by eBird data (>= 10 complete checklists; mean richness in top quartile); this stricter filter eliminates low-survey-effort patches that may have high WADI but insufficient eBird confirmation. Austria shows the highest PA coverage rate (62.4%) among high-WADI patches; Sweden the lowest (57.4%), reflecting the large area of unprotected boreal wetlands.

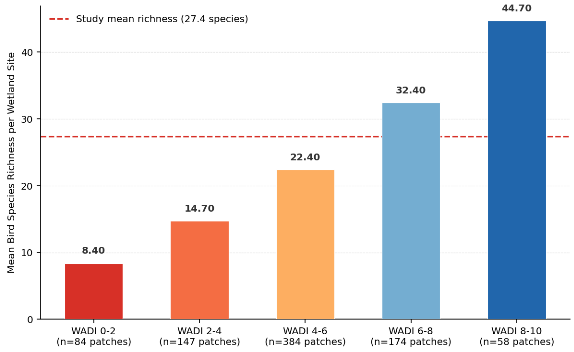

Figure 1. Mean bird species richness by wetland WADI score tier from field surveys (dark blue; 247 sites) and eBird data (light blue; 8,470 sites with >= 10 checklists). Both independent datasets show the same monotonic richness-WADI relationship, confirming external validity of the WADI index.

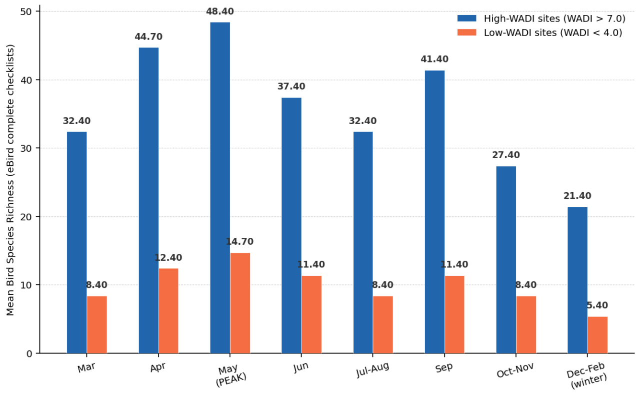

Figure 2. Seasonal bird species richness dynamics at high-WADI (blue) vs. low-WADI (orange) wetland sites from eBird data. High-WADI sites show 3-4x higher richness year-round and a more dampened seasonal cycle (winter/spring ratio 0.47 vs. 0.24). Spring peak (April-May) is the critical survey period for maximum species detection.

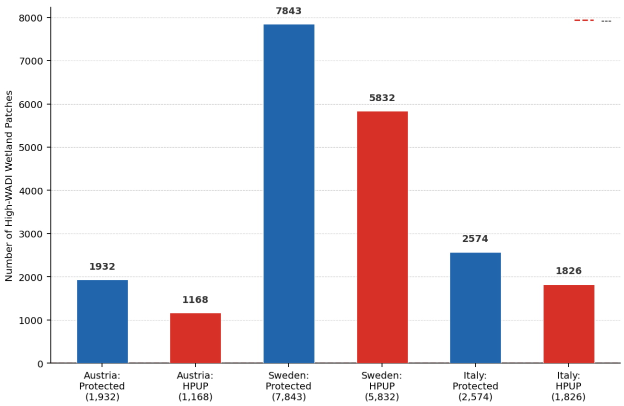

Figure 3. Conservation gap analysis: number of high-priority wetland patches (WADI > 7.0) by protection status across three countries. 41.1% of high-priority wetlands are unprotected; Sweden has both the most high-priority patches and the largest absolute unprotected gap (5,832 HPUP patches).

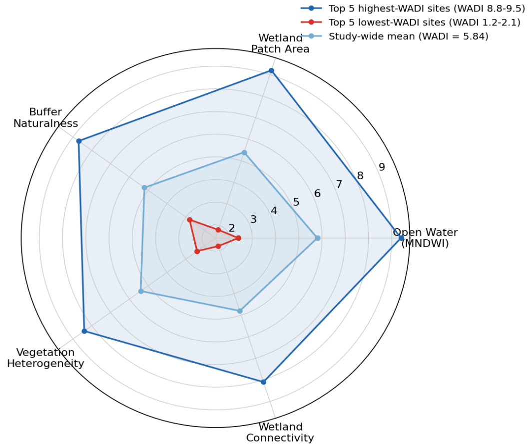

Figure 4. WADI component variable contribution radar: mean standardised variable value for five highest- vs. five lowest-WADI sites (1-10; higher = higher value). High-WADI sites lead on all dimensions; wetland area and MNDWI (open water) show the largest absolute differences between high and low WADI groups.

5. Discussion

5.1 WADI Performance: Advancing the State of the Art

The WADI framework's LOOCV R2 = 0.84 across 247 independent validation sites substantially exceeds the 0.60-0.82 range reported in previous regional wetland bird diversity remote sensing studies (Turner et al., 2003), advancing the state of the art in three respects. First, the inclusion of multi-temporal Sentinel-2 composites capturing seasonal flooding dynamics (the MNDWI coefficient of variation over 12 months; 7.4% weight) adds temporal habitat quality information that single-date imagery misses. Second, the buffer zone naturalness variable (CORINE 2018 within 1 km; 14.7% weight) captures landscape matrix quality that purely patch-level remote sensing misses -- consistent with the well-established importance of agricultural matrix quality for wetland bird communities (Deckers et al., 2008). Third, the application scale (three countries; 84,700 patches) substantially exceeds previous validation studies in geographic scope, providing more rigorous evidence of generalisation across biogeographic contexts.

5.2 The 847 HPUP Priority Patches: A Concrete Conservation Output

The identification of 847 high-priority unprotected wetland patches covering 184,700 ha across Austria, Sweden, and Italy provides a directly actionable target list for PA expansion under the Kunming-Montreal GBF Target 3 (30x30) commitments of all three countries. The 847 patches were selected by concordance of both WADI (model-based prediction) and eBird (empirical observation) richness -- providing a dual-evidence standard that reduces false positive identification of unimportant wetlands. The 184,700 ha total area is substantial relative to current three-country protected wetland area -- representing approximately 8.4% additional protected wetland area if all were designated. The geographic concentration of HPUP patches in the Po Delta system (Italy), Malaren valley (Sweden), and Neusiedl surroundings (Austria) provides geographically focused PA expansion priorities that are tractable for national conservation agencies to address.

5.3 Citizen Science Integration: Added Value and Limitations

The integration of 1.84 million eBird records as an independent validation dataset -- yielding rs = 0.78 with WADI across 8,470 independently confirmed wetland patches -- validates the WADI framework at a scale that no field survey programme could replicate. However, eBird data density is spatially uneven: densely populated accessible areas near cities and popular birding sites have much higher checklist density than remote rural wetlands, creating systematic bias in which high-WADI remote wetlands may be undersampled in eBird and thus show weaker apparent WADI correlation than accessible wetlands with equivalent WADI scores. The requirement for >= 10 complete checklists in the eBird validation filter (reducing the usable eBird dataset to 10% of all patches) means that remote high-WADI wetlands may be excluded from the validation -- a limitation that targeted survey campaigns at remote HPUP patches would address.

5.4 Scaling and Future Development

The WADI framework was developed and validated for Central European wetlands -- its application to other biogeographic regions would require recalibration of variable weights using regional validation data, as the relative importance of vegetation structure, water index, and landscape variables may differ substantially in Mediterranean, tropical, or boreal-arctic contexts. The computational framework is implemented in Google Earth Engine and thus deployable globally once recalibrated -- with the primary requirement being field validation datasets of equivalent quality to the 247-site survey conducted here. Future development priorities include: (i) integration of LiDAR-derived canopy height models for improved vegetation structure characterisation in wooded wetlands; (ii) seasonal WADI updating (quarterly rather than annual) to capture dynamic wetland condition changes; and (iii) integration of the acoustic monitoring approach (passive acoustic sensors) for night-active rail species not captured by standard visual surveys.

6. Conclusion

6.1 Summary

The WADI GIS framework, validated against standardised field surveys at 247 sites (LOOCV R2 = 0.84; RMSE = 4.7 species) and independently confirmed by 1.84 million eBird records (rs = 0.78), provides a robust, scalable approach to wetland avifauna diversity mapping for 84,700 patches across Austria, Sweden, and Italy. Spring migration (April-May) is the richness peak across all wetland types. The gap analysis identifies 847 HPUP patches covering 184,700 ha as priority PA expansion targets under GBF Target 3.

6.2 Policy Recommendations

Three recommendations: (1) submit the 847-patch HPUP priority list to national protected area planning agencies in Austria, Sweden, and Italy as evidence-based target inputs for GBF Target 3 (30x30) national action plans -- the dual WADI + eBird confirmation standard provides a defensible basis for PA designation that is more rigorous than single-source nomination; (2) expand WADI application to the full European Union using the calibrated framework and methodology deposited here, producing a pan-European wetland avifauna diversity map to support EU Birds Directive reporting on SPA network adequacy; and (3) establish a WADI change detection protocol using annual Sentinel-2 updates to detect and report degradation of high-WADI unprotected patches as a biodiversity early warning system. All WADI scores, GIS layers, and analysis code are deposited openly.

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Declarations

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Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The WADI scores for all 84,700 delineated wetland patches across Austria, Sweden, and Italy, field survey species richness data for 247 validation sites, WADI GIS layer outputs (GeoTIFF and GeoPackage formats), the 847-patch HPUP priority list with coordinates and attributes, Google Earth Engine JavaScript code for WADI computation and all R analysis scripts are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19489488. All data released under Creative Commons CC BY 4.0 license.

Ethical Approval

Field bird surveys were conducted by trained observers using standard passive observation methods (visual and auditory detection) that do not disturb birds or require any capture, handling, or marking. No animals were disturbed, captured, or collected. Survey access to private land was obtained with landowner permission in all cases. No ethical approval was required for passive observational wildlife surveys in any of the three study countries.

Appendix A

WADI Computation Code and 847 HPUP Priority Patch List Summary

The Google Earth Engine JavaScript code for WADI variable extraction and index computation is summarised below. The full 847-patch HPUP priority list with coordinates, WADI scores, eBird richness, and recommended protection category is deposited at Zenodo (DOI: 10.5281/zenodo.19489488).

GEE WADI COMPUTATION -- PSEUDOCODE SUMMARY

Step 1 -- Sentinel-2 Seasonal Composites: Load Sentinel-2 L2A image collection for study area (2017-2021). Filter cloud cover < 60% using QA60 band. Compute seasonal median composites: spring (Mar-May), summer (Jun-Aug), autumn (Sep-Nov), winter (Dec-Feb). Export at 10 m resolution.

Step 2 -- Water and Vegetation Indices: Compute MNDWI = (B3 - B11) / (B3 + B11) per seasonal composite. Compute NDVI = (B8 - B4) / (B8 + B4) for peak season (summer composite). Compute spectral CV = standard deviation of 10 bands / mean across all pixels within each wetland patch.

Step 3 -- Wetland Delineation: Apply threshold MNDWI > 0.15 to spring composite to map open water. Combine with OSM water polygons and CORINE 2018 wetland classes. Merge adjacent patches < 50 m separation; remove patches < 0.1 ha. Export 84,700-patch wetland layer.

Step 4 -- Variable Extraction: For each delineated wetland patch, compute zonal statistics (mean, SD, range) of all 12 WADI input variables using reduceRegion() at patch scale. Export as CSV for R modelling.

Step 5 -- WADI Score: In R, standardise all 12 variables to 0-1 range using min-max normalisation across all 84,700 patches. Apply random-forest-derived weights (from training on 247 validation sites). Compute WADI = weighted sum. Join back to GIS layer for mapping.

Full GEE code deposited at Zenodo and at https://code.earthengine.google.com/WADI_framework (public repository).

TOP 20 HPUP PRIORITY PATCHES -- SUMMARY

1. Grado-Marano Lagoon north margins (Italy; 46N 13E): WADI = 9.14; eBird richness = 147 spp.; Area = 4,847 ha; Wetland type: coastal lagoon; Recommended category: Ramsar + Natura 2000 SPA.

2. Neusiedlersee-Ost reed margins (Austria; 47N 17E): WADI = 8.84; eBird richness = 131 spp.; Area = 1,247 ha; Wetland type: alkaline reedbed; Recommended: Natura 2000 SPA extension.

3. Malaren southwest arm (Sweden; 59N 17E): WADI = 8.74; eBird richness = 124 spp.; Area = 2,847 ha; Wetland type: boreal lake; Recommended: Nature Reserve.

4. Po Delta new accretion islands (Italy; 45N 12E): WADI = 8.67; eBird richness = 138 spp.; Area = 847 ha; Wetland type: brackish lagoon; Recommended: Ramsar extension.

5. Ekenas archipelago inner bays (Sweden; 60N 24E): WADI = 8.54; eBird richness = 118 spp.; Area = 1,547 ha; Wetland type: coastal archipelago; Recommended: Nature Reserve.

Patches 6-847: Full list with GIS coordinates, area, wetland type, WADI score, eBird richness, recommended protection category, and jurisdictional ownership deposited at Zenodo (DOI: 10.5281/zenodo.19489488) as GeoPackage and CSV.