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Method Article

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A GIS-based framework for standardized environmental characterization in One-Health surveillance: a case study of HPAI monitoring in wetlands

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Abstract

Background
The Highly Pathogenic Avian Influenza (HPAI) panzootic caused by H5 viruses of clade 2.3.4.4b is constantly re-shaping disease ecology in terms of spatio-temporal spread and host spectrum. Because of this, there is an increasing need to complement traditional surveillance methods with approaches that consider environmental factors into epidemiological interpretation. Although environmental surveillance is increasingly recognized within a One Health framework, environmental descriptors are not always consistently structured, underscoring the importance of adopting standardized approaches for their collection and management.

Method
A GIS-based framework was developed to standardize environmental characterization of HPAI surveillance sites. Environmental data were collected at nine wetlands in north-eastern Italy, using ESRI field map tool, synchronised through ArcGIS online. Data were validated with field-base ground truthing, stored in a spatial relational database and aggregated into harmonised site-specific descriptors, suitable for epidemiological modelling and analyses.

Results
This study introduces a GIS-based framework designed to standardize how environmental features are recorded at sampling sites for HPAI surveillance. The workflow turns different types of field observations into organized geographical datasets that can be analysed. When used at wetland surveillance sites in north-eastern Italy, this framework produced consistent environmental data and standardized records for each site.

Conclusions
The workflow combines mobile GIS tools (ESRI Field Maps), ArcGIS Online/Pro, and a PostGIS database to create standardized outputs for epidemiological analysis. This setup creates a reliable connection between field ecology, spatial data infrastructures, and disease risk analysis.

Keywords; HPAI, Environment, GIS, Wild birds, One Health, Wetland

Background

Emerging infectious diseases (EIDs) represent one of the major challenges to global health, biodiversity conservation, food security, and economic stability. Over recent decades, the frequency and geographic extent of disease emergence events have increased, driven by complex interactions among pathogens, hosts, and rapidly changing environmental conditions [1]. Factors such as land-use, habitat disruption, climate variability, agricultural intensification, globalization, and increasing connectivity between wildlife, domestic animals, and humans can influence pathogen transmission dynamics and create new opportunities for disease emergence and spread [2]. As a result, disease occurrence is the sum of interactions occurring among populations within specific ecological, environmental and socio-economical contexts.

In response to this growing complexity, the One Health approach has emerged as a conceptual framework promoting the integration of human, animal, and environmental health to better understand, prevent, and

manage infectious disease threats [3]. Within this framework, the environment is no longer viewed as a surrounding element where disease transmission occurs, but as an active component influencing pathogen persistence, host distribution, transmission pathways, and exposure risk [4]. Consequently, effective surveillance systems require not only the detection of pathogens and infected hosts, but also the systematic characterization of the environmental conditions in which pathogen circulation and transmission occur.

Among contemporary EIDs, HPAI caused by clade 2.3.4.4b H5Nx viruses stands as one of the most significant animal and public health concerns worldwide. Since the emergence of these viruses in late 2013, HPAI has undergone major epidemiological changes, resulting in an unprecedented geographic expansion and recurrent epidemic waves affecting wild and domestic bird populations across multiple continents [5] [6] [7]. Regions characterized by dense poultry production, extensive wetland systems, and major migratory flyways have experienced particularly severe impacts [8] [9]. Beyond its consequences for animal health and poultry production, the 2.3.4.4b clade has progressively expanded its host range causing infections in numerous mammalian species including humans, raising concerns regarding its zoonotic potential [10]. In Europe, repeated epizootic events have contributed to the year-round persistence of 2.3.4.4b H5Nx viruses within wild bird populations, fundamentally altering the epidemiological landscape of the disease [11].

These changes in the ecology and epidemiology of HPAI have challenged traditional surveillance systems, which have historically relied on active and passive surveillance of wild birds for early detection and monitoring the circulation of Avian Influenza Viruses (AIVs) [12]. Although these strategies remain essential, they may be limited by logistical constraints, uneven spatial coverage, and the difficulty of adequately monitoring all relevant host species and habitats [13].

Environmental sampling has recently gained attention as a promising and cost-effective strategy to complement animal-based surveillance [14]. Over the years, a variety of environmental samples have been investigated for AIV detection in wild habitats, including faeces, water, sediment, soil, and feathers [15] [16] [17]. Insects have also been investigated as potential mechanical vectors of avian influenza viruses, following sporadic detections of viral material in insect specimens collected in areas affected by outbreaks or in association with infected wild birds [18] [19] [20]. Recently, novel passive sampling strategies based on floating torpedo-shaped devices containing adsorbent materials and deployed in water bodies to capture viral particles [21] showed enhanced sensitivity in detecting AIV in wild ecosystems, and provided early warning for AIV/H5 2.3.4.4b circulation [22].

Despite increasing interest in environmental sampling, most studies have focused primarily on evaluating their utility in terms of virus detection capacity [23] while giving limited attention to the environmental context in which these samples were collected. Relevant factors such as wetland morphology, land cover, vegetation structure, hydrological connectivity and human activities may influence pathogen persistence, host aggregation, detection probability, transmission dynamics, and disease risk. The lack of such contextual data limits the ability to investigate ecological drivers of pathogen occurrence and hampers comparisons across studies and surveillance programs [24] [25] [26]. The challenge, however, extends beyond the mere collection of environmental information. To be effectively incorporated into epidemiological studies, on-field environmental data must be systematically acquired, standardized, stored, managed, and transformed into analytical variables suitable for statistical modelling and spatial analysis. While satellite-derived environmental datasets provide valuable broad-scale coverage, local-scale observations can provide complementary information on habitat features and ecological conditions, contributing to a more detailed understanding of the environmental factors that may influence pathogen occurrence. Ground-based observations are therefore necessary to capture fine-scale environmental heterogeneity and to assess how local environmental conditions correspond to, or differ from, patterns identified through remotely sensed data and to validate remotely sensed information at the local scale.

Geographic information systems (GIS) provide a powerful framework for addressing these challenges by managing the full workflow from field observations to the generation of spatial variables. Beyond their traditional role in visualization and mapping, GIS can offer a structured and repeatable process for collecting, validating and integrating spatial data, managing geodatabases, and producing standardized outputs for epidemiological studies [27] [28]. This infrastructure improves data acquisition, quality control, and harmonization, while ensuring the consistent derivation of spatial covariates. In the context of HPAI surveillance, GIS can help bridge the gap between animal and environmental surveillance activities and the analytical requirements of disease ecology and epidemiology. To address this need, this study presents a GIS-based framework designed to standardize environmental characterization around HPAI environmental sampling sites and to generate a structured spatial dataset of relevant covariates suitable for epidemiological analyses. Using environmental sampling data from north-eastern Italy as a case study, the framework supports the systematic collection, management, and integration of environmental information associated with sampling locations. By transforming field and environmental observations into standardized spatial variables, the proposed approach aims to enhance the epidemiological value of environmental sample data and facilitate future investigations into the ecological drivers of AIV circulation, persistence, and detection.

Methods

To support the management of the entire field data collection workflow, a dedicated GIS framework was designed. The framework was conceived as an integrated ecosystem aimed at ensuring data continuity from field acquisition through data validation, offering a final dataset that can be flexibly adapted to generate different outputs depending on the downstream analysis.

The framework was structured around three core pillars (figure 1): i) data acquisition suite for operational geospatial data collection and management; ii) a relational spatial database for data storage, persistence, and harmonization; and iii) output production for the Field Assessment Report generation and the creation of a standardized final dataset. For the sake of the present study, the workflow is presented up to the generation of the final dataset, while subsequent epidemiological modelling applications are beyond the scope of this work.

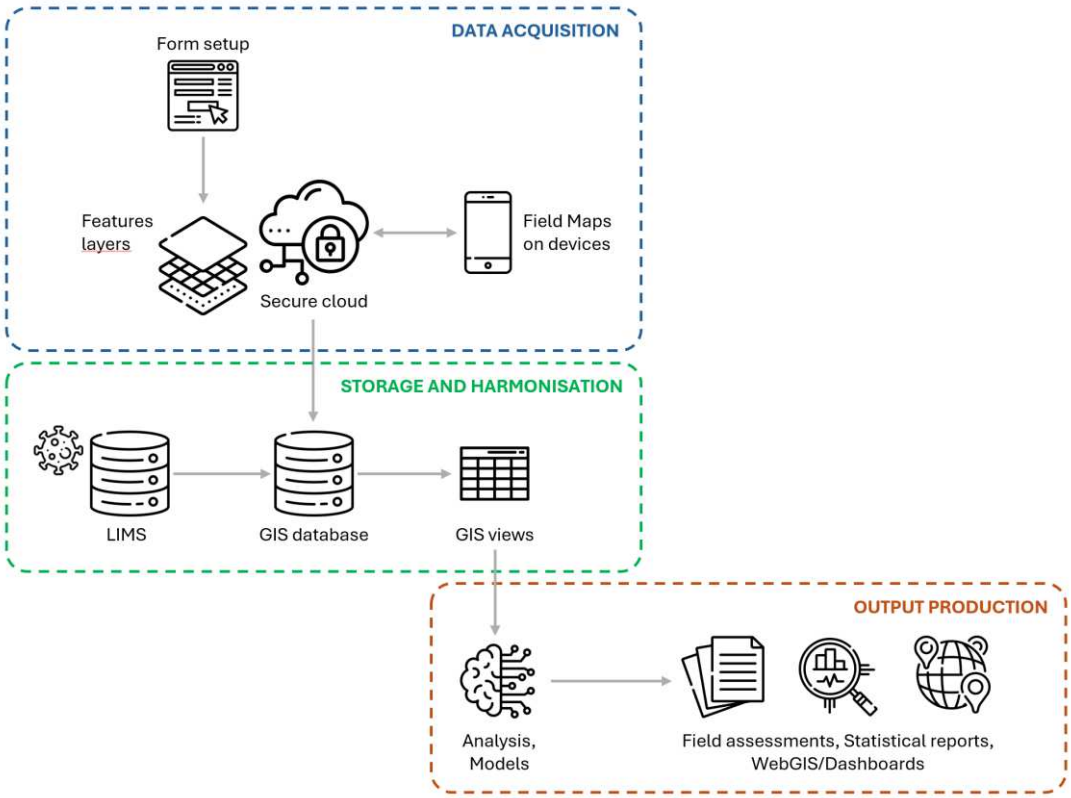


Fig. 1 Graphical schema of the entire framework, subdivided in the three core pillars.

2.1 Study Area

The Province of Verona lies in the Veneto region, in north-eastern Italy, and it is divided into two major landscape areas: the northern part features mountainous terrain, while the southern part extends into the Po Plain, a highly anthropised environment shaped by a mosaic of intensive agricultural areas, urban and peri-urban settlements, road infrastructures and farms [29]. This southern area represents a major hub for the Italian poultry sector, encompassing one of the country's most densely populated poultry areas (DPPA), and it is further characterized by the presence of a large number of wetlands that serve as habitat for various wild birds' species, including Anseriformes. These ecological and productive features have made the study area particularly vulnerable to recurrent epidemic waves of HPAI, which over the past decade have severely impacted its socio-economic system [30].

2.2 Data model

The information used to characterize the territory encompasses multiple environmental components that can be represented within a GIS framework through different modelling approaches. In this context, these components were implemented as vector features with attribute schemas specifically designed to capture the characteristics of interest. The overall aim was to develop a structured dataset in which each wetland is associated with a unique and standardized set of environmental and territorial descriptors.

The main entities were:

- **Wetland:** Defines the area of relevance surrounding each water body within which sampling activities were conducted. Originally derived from the water bodies themselves, the final areas were delimited by natural or anthropogenic features like roads, forests, or urban areas. These entities were represented using polygon primitives.

- **Water element:** Water bodies selected for their dimensions and locations in the study area. Natural water bodies were considered, excluding lagoonal or fluvial elements. Multi-polygon geometrical primitives were adopted for these entities, and manual digitalization was applied when needed to reflect actual morphology discovered during ground-truthing.

- **Territorial Element:** This object identified micro-habitats, including land cover, based on the updated Corine Land Cover 2018 classes at the third level [31], vegetation, shoreline morphology, bird defecation/resting zones, anthropic access points, and infrastructure related to the water elements (hydraulic doors). Represented as a point primitive, those entities covered different aspects of the environmental aspects of the area.

- **Sampler:** This object represents the precise sampling location, such as: water samples, faecal samples, water samples for physical and chemical analysis, and mosquito traps for entomological studies. They were represented with a point primitive.

- **Administrative boundaries:** Provinces and Municipalities boundaries represented as multi-polygons. The dataset was sourced from National Institute of Statistics (ISTAT) [32], providing high-resolution official administrative divisions of Italy for the year 2025.

2.3 Data Acquisition suite setup

The GIS environment was structured to ensure interoperability between mobile, web, and desktop platforms through a centralized feature service. A set of pre-defined layers were set up to produce context layers and editable layers.

The context layers allow the operator to understand the determine study area localization and define the main geographical and administrative characteristics of the surrounding territory. The entities used for this aim were the water element and the administrative boundaries.

The water elements initial dataset was sourced from OpenStreetMap (OSM) [33] via the QuickOSM plugin [34] in QGIS. The area of interest was defined as the Verona province in the Veneto Region. The OSM query extracted *natural = 'water'* features, each identified by a unique *osm_id*, yielding approximately 1,500 elements. The dataset was then filtered to remove fluvial elements and non-relevant features, including water bodies outside the 1,250 km^2 – 10 km^2 range, resulting in 416 features. From this refined dataset, 9 water bodies were selected based on criteria relevant to Avian influenza virus detection, such as abundance distributions of relevant reservoir/bridge wild bird species selected based on Martelli et al. (2025) [35] and the proximity to previous HPAI detections [36]. These 9 features were subsequently used to delineate and develop the corresponding wetland areas. In addition, a set of basemaps and satellite imagery was selected to add further geographic details and facilitate user interaction during the on-field activities.

The editable layers were designed to support user interaction with the dataset, adding the environmental and territorial elements to describe the presence of surrounding entities, i.e. wetlands, territorial elements and samples. For each of them a dedicated form was developed.

The wetland layer was originally obtained by applying a 30-meter buffer around water elements. Then these initial polygons were reshaped and adapted based on the directly observed geographic features of the environment, such as roads, property boundaries, and existing natural water elements, to better reflect the real spatial extent of each wetland area. All the features were identified by a unique *wet_id*, assigned during creation and a set of descriptive attributes capturing site characteristics was defined: hunting or fishing activities, bird species presence, and human disturbance indicators. The full set of attributes is presented in *Table 1*.

Table 1 Wetland structure.

Attribute	Type	Description
wet_id	string	The unique identifier for wetlands.
w_name	string	Geographical or local name of the wetland.
ownership	string	Ownership type (*public; private*).
w_type	string	Hydrological typology of the wetland *(spring-fed; rain fed; river-fed*).
w_origin	string	Origin of the wetland (*natural; artificial; restored*).
protected	string	Whether the wetland is subject to environmental protection measures, legal restrictions, or conservation regulations.
fenced	boolean	Whether the wetland area is enclosed or protected by a fence.
anthr_pres	boolean	Indicates the presence and intensity of human activities or infrastructure within or near the wetland area.
hunting	boolean	Indicates whether hunting activities are present or have been reported in or around the wetland area.
fishing	boolean	Indicates whether fishing activities are present or occur in the wetland or associated water bodies.
bird_sights	string	List of bird species observed within or around the wetland area during field activities (e.g.: *Grey Heron*; *Mallard duck*; *Great Cormorant*).

notes	string	Free-text field used to record additional observations, comments, or relevant information.

For the Territorial Elements, the form requires the wet_id of the associated site and provides a set of general descriptive fields. Conditional logic was used to adapt the form based on the type of element recorded, distinguishing between categories such as Corine Land Cover (CLC) descriptors, islands, hydraulic structures, or access points. In the case of CLC-type "shoreline" elements, additional fields are enabled to describe shoreline type and associated vegetation characteristics. The full set of attributes is presented in Table 2.

Table 2 Territorial element structure.

Attribute	Type	Description
obj_id	string	The unique identifier for territorial elements.
wet_id	string	The unique identifier for wetlands used to link territorial elements to the corresponding wetland area.
el_terr	string	Type of geographic feature detected (e.g.: CLC; *access point*; *hydraulic gate*).
clc	string	If the territorial element describes a land cover aspect, it contains a specific CLC class.
date	date/time	Date and time on which the field survey was conducted.
shore	boolean	Whether the detected CLC element is located along the wetland shore or not.
slope	string	Indicates the slope class of the wetland shore. Classified according to shore slope categories as defined in [37]: *gentle (≤20°)*; *moderate (> 20° to ≤ 45°)*; *steep (> 45°)*.
shore_veg_h	numeric	Indicates the average height of the shore vegetation measured at the surveyed point.
notes	string	Free-text field used to record additional observations, comments, or relevant information.
attachments	attachment	Collection of files attached to the feature (e.g.: JPG images acquired during field activities).

The sampler form was designed to support different sampling types. Users can classify the sample type (e.g. mosquito, water sample, or faecal sample). Based on this selection, conditional (dynamic) fields are shown or hidden to capture relevant contextual information. Additionally, an automatic unique identifier was generated using key attributes such as sampling date, site identifier (*wet_id*), and sample type (e.g. *site_01_ps1_20251124*), ensuring traceability and consistency across records. The full set of attributes is presented in *Table 3*.

Table 3 Sample structure.

Attribute	Type	Description
smp_id	string	The unique identifier for samples.
wet_id	string	The unique identifier for wetlands used to link territorial elements to the corresponding wetland area.

samp_type	string	Type of sample collected at the location (*Mosquitoes, Water sample, water sample for physical and chemical analysis, Faecal sample*).
code_lab	string	Descriptive code used by the laboratory to identify the sample type or analytical category (e.g., "hy" for water sample for physical and chemical analysis). Intended for internal use within and collaborating laboratories.
date_start	date/time	Date and time on which samplers for water and mosquitoes are positioned in the field; if no devices are required, it coincides with the sample collection date.
date_end	date/time	Date and time on which samples for water, mosquitoes and fecal samples are collected.
municipality	string	Municipality name in which the sampling is collected.
istat	string	Official code assigned by ISTAT identifying the municipality where the sampling point is located. Municipalities change during the time, merging or splitting. Even though the name could be maintained, the code changes according to each modification.
samp_code	string	Unique identifier for each sample, generated by concatenating the wet_id, laboratory code, and sampling start date.
pH	numeric	Measured pH value of the water sample recorded in the field at the time of sampling.
w_temp_max	numeric	Highest temperature recorded at the passive water sampler location during the field survey or sampling period.
w_temp_max	numeric	Minimum temperature recorded at the passive water sampler location during the field survey or sampling period.
w_turbidity	string	Qualitative assessment of water turbidity observed in the field based on visual inspection, classified using descriptive method (*low*; *medium*; *high*).
algae	string	Indicates the presence and abundance of algae observed in the water at the sampling point, classified using descriptive method (*low*; *medium*; *high*).
w_moves	boolean	Indicates whether the water at the sampling point is stagnant or in motion.
notes	string	Free-text field used to record additional observations, comments, or relevant information.

The ESRI Field Maps Designer [38] was used to design and configure the data collection workflow and the user interface for field surveys. The tool enables the creation of online geographical layers, each configured with a predefined attribute schema to record field observations, which can then be deployed within a dedicated map composition available on mobile devices for real-time data capture. Through this tool, each layer was visible on the map and could be edited through a tailored data entry form optimized for field data collection, with fields and conditional logic aligned to the specific type of information required.

To support the researcher during field operations, a set of geofences was configured based on the boundaries of the "Wetlands" layer. By leveraging the device's Global Positioning System (GPS), the

application generates automatic notifications when entering or exiting these virtual boundaries, guiding operators in real time and reducing the risk of incorrect site attribution or sampling errors.

2.4 Field operations and data validation

The research focused on nine selected wetlands in the Verona province, identified as strategic locations for environmental and entomological sampling, as well as for avian influenza virus detection as part of an ongoing surveillance study.

Operational activities were preceded by a planned reconnaissance survey on 2025, 25 August, conducted jointly with veterinary personnel, with the aim of testing sampling procedures, evaluating the usability of digital forms, and validating the spatial data synchronization workflow.

Field activities were organized as recurring biweekly sessions during the period September – December 2025. Operational planning optimized road access, site accessibility, and temporal coverage, typically including two wetlands per field mission for environmental characterization activities. During each field session, the GIS operator recorded geolocation of water samples, faecal samples, water samples for physical and chemical analysis, mosquito traps and territorial characteristics focusing on the collection of information describing the environment surrounding each water body. If needed, wetland attributes were also updated.

The pre-defined set of digital forms were completed using the Field Maps app freely available for Android [39] and IOS [40]. An example of the final user interfaces for Android devices were reported in Figure 2.

Simultaneous synchronization through different apps in the ArcGIS Online platform [41] allowed real-time verification of acquired data and immediate detection of potential spatial inconsistencies. Direct field observations were used to verify the consistency between available geospatial datasets and actual environmental conditions at each site. In cases where discrepancies were detected, topological corrections were applied. These corrections could include manual digitization of missing geometries, modification of existing polygons to reflect observed morphology, and reinterpretation of features initially misclassified in remote source datasets.

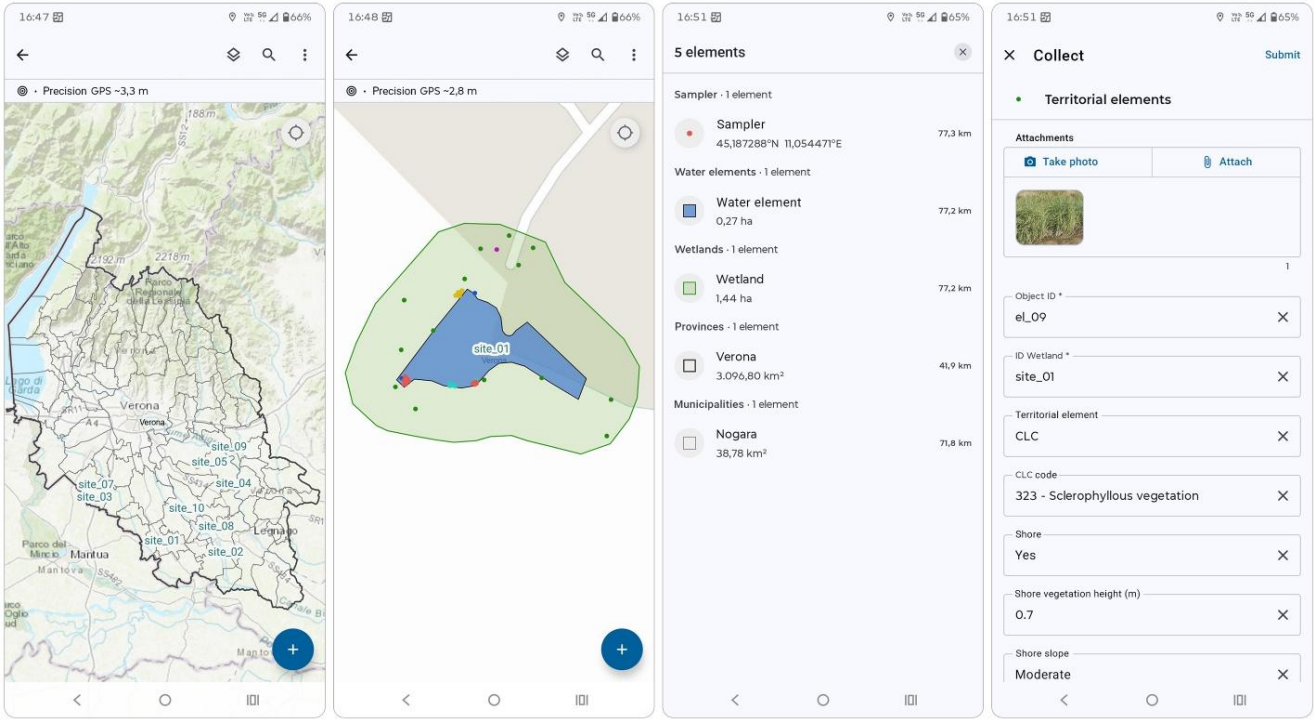


Fig. 2 ESRI Field Maps app user interfaces: examples of the interactive map, available layers and digital form for editing operations.

2.5 Post-acquisition operations

Following data acquisition, data produced were stored in the online platform. The original structure generated multiple records of territorial/environmental elements or samples for each wetland, which is not suitable for reporting or for analytical purposes.

To address this, data-views were defined to aggregate elements according to the needs. In particular, a view dedicated to the description of environmental characteristics was implemented to aggregate observations to derive harmonized descriptors at the wetland level. This approach generated a structured "ready-to-use" dataset in which each wetland corresponded to a single analytical record associated with multiple derived environmental covariates. Several data-views could be defined according to purposes such as statistical reports or laboratory results.

To easily manage data for further extractions and analyses, a dedicated database was implemented. The original features, defined as *feature layers*, were structured within the database as relational tables that mirror the data collection layers used in the field. The main tables include:

- **sampler**: Represents the sampling points and monitoring devices. It includes records related to the deployment of passive water samplers for avian influenza virus detection in water, entomological traps (mosquito traps), and locations of faeces and water samples for physical and chemical analysis collection.
- **territorial_elements**: Describes point-based micro-habitat characterization. It stores data on land use according to the CLC classification (e.g., vegetation, roads, watercourses), as well as the presence of morphological islands, avifauna roosting and defecation areas, anthropogenic access points, and hydraulic infrastructure.
- **wetland_sampling_areas**: A polygon-based definition of the boundaries and general characteristics of sampling areas around the wetlands. It aggregates information collected across multiple field campaigns, enabling a comprehensive and standardized description of each area.

Data flows from the online storage to a well-structured spatial geodatabase in PostgreSQL Relational Database Management System [42] with a PostGIS extension [43]. The structure of the database is reported in *Figure 3*.

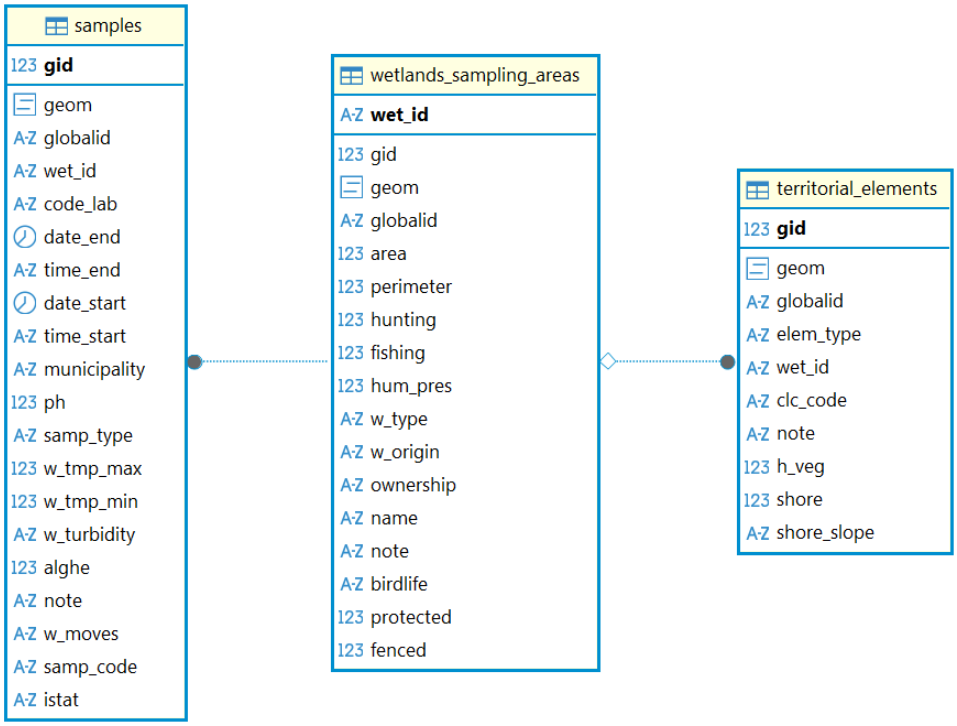


Fig. 3 The main tables that constitute the database structure. Each table contains a set of fields, the primary key (in bold) and the relationships with other tables (1 wetland may have N sample, 1 wetland may have N territorial elements).

Within this database, a process of data enrichment was implemented to automatically integrate data from laboratory testing for AI/HPAI obtained from Istituto Zooprofilattico Sperimentale delle Venezie (IZSVe) Laboratory Information Management System (LIMS).

A set of static maps was generated for each area representing the wetland and the observed surrounding territorial elements, and the sampling points. Maps were produced using ArcGIS Pro [44].

A comparison between *in situ* observations and existing publicly available datasets (e.g., OSM and CLC) was conducted, revealing several discrepancies particularly relevant at the micro-scale level.

These outputs were integrated into a set of standardized field assessment reports, combining maps and text to provide a structured description of the environmental characteristics of each area. The harmonized output generated through the database data-view was exported as a spreadsheet and uploaded into a NotebookLM [45] project to produce *data-driven* textual descriptions. The GIS operator then reviewed and validated the generated content and, once finalized, integrated the textual descriptions with the corresponding cartographic outputs to produce the final site documentation.

Results

The primary result was the generation of a harmonized analysis-ready output. Through aggregation of repeated observations, each wetland was represented as a single analytical unit associated with standardized environmental attributes. This structure addresses fragmentation inherent in raw field data and allows the integration of laboratory testing results associated to the sampled site. The resulting dataset was designed to support downstream spatial and temporal analyses for further epidemiological analysis. The views were dynamically updated following insertions or modifications in the database tables and are available within the IZSVe network for scientists and researchers. The full structure of the view is reported in Table 4.

Table 4 Database view structure to describe environmental characteristics.

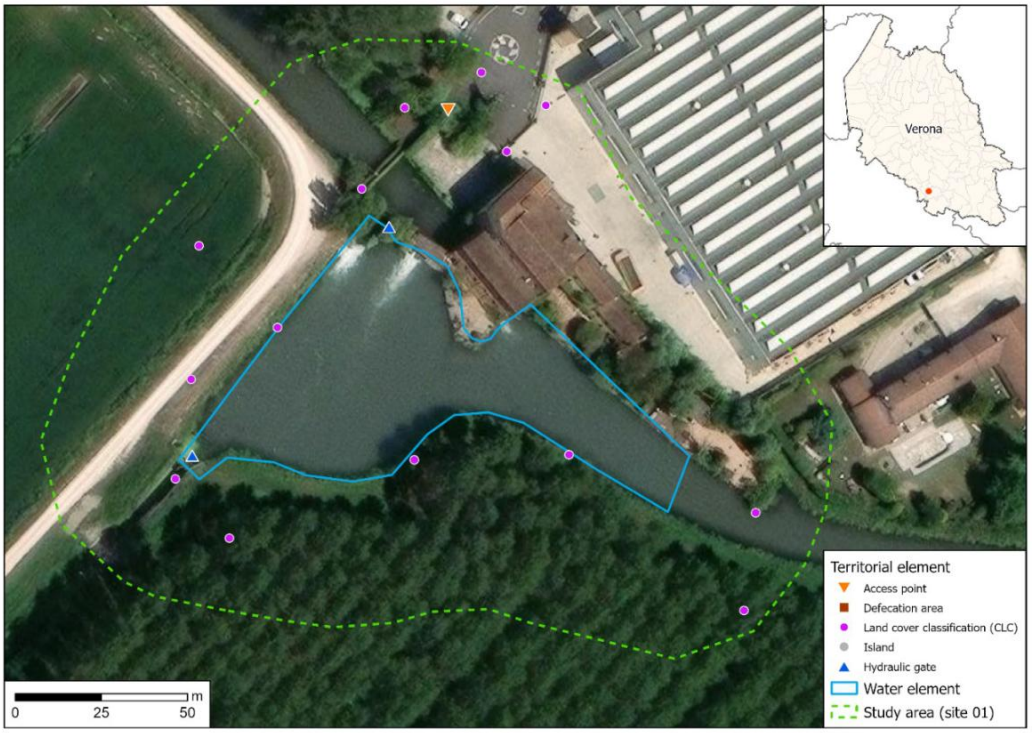
Field	Type	Description
wet_id	string	The unique identifier for wetlands.
name	string	Geographical name of the wetland, like local name.
w_type	string	Hydrological typology of the wetland *(spring-fed; rain fed; river-fed*).
w_origin	string	Origin of the wetland (*natural; artificial; restored*).
ownership	string	Ownership type (*public; private*).
protected	boolean	Whether the wetland is subject to environmental protection measures, legal restrictions, or conservation regulations.
fenced	boolean	Whether the wetland area is enclosed or protected by a fence.
hunting	boolean	Indicates whether hunting activities are present or have been reported in or around the wetland area.
fishing	boolean	Indicates whether fishing activities are present or occur in the wetland or associated water bodies.
human_presence	boolean	Indicates the presence and intensity of human activities or infrastructure within or near the wetland area.
birdlife	string	List of bird species observed within or around the wetland area during field activities (e.g.: *Grey Heron*; *Mallard duck*; *Great Cormorant*).
area_sqm	numeric	Total surface of the wetland area expressed in square meters (m^2).
perimeter_m	numeric	Total perimeter of the wetland area expressed in square meters (m^2).
n_terr_elem	numeric	Number of territorial elements collected in the wetland area.
n_elem_types	numeric	Number of territorial elements identified and collected within the wetland area during the survey.
h_shore_veg_min_m	numeric	Minimum-recorded value of the average vegetation height along the pond shores within the wetland area, expressed in meters (m).
h_shore_veg_max_m	numeric	Maximum-recorded value of the average vegetation height along the pond shores within the wetland area, expressed in meters (m).
slope_min_class	string	Minimum-recorded value of the slope class along the pond shores within the wetland area (*gentle, steep, moderate*).
slope_max_class	string	Maximum-recorded slope class observed along the pond shores within the wetland area classified according to shore steepness categories (*gentle, moderate, steep*).
has_accesso	boolean	Boolean flag indicating whether the wetland area includes at least one point of access for humans and vehicles.
has_hydraulic_gate	boolean	Boolean flag indicating whether the wetland area includes at least one hydraulic gate connected to the pond.
has_defecation_site	boolean	Boolean flag indicating whether the wetland area includes at least one bird's defecation site.
has_island	boolean	Boolean flag indicating whether the wetland area includes at least one island in the pond
clc_111	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC111 (continuous urban fabric).
clc_112	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC112 (discontinuous urban fabric).

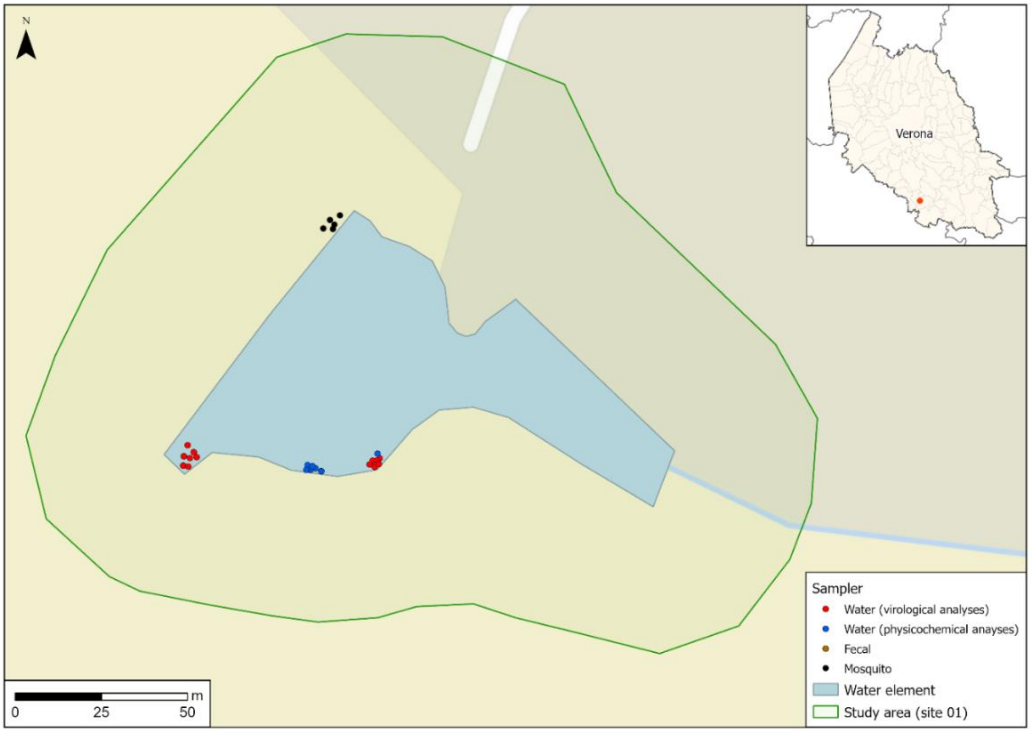
clc_121	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC121 (industrial or commercial units).
clc_122	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC122 (road and rail networks and associated land).
clc_123	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC123 (port areas).
clc_124	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC124 (airports).
clc_211	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC211 (non-irrigated arable land).
clc_212	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC212 (permanently irrigated land).
clc_213	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC213 (rice fields).
clc_231	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC231 (pastures).
clc_242	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC242 (complex cultivation patterns).
clc_243	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC243 (land principally occupied by agriculture, with significant areas of natural vegetation).
clc_311	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC311 (broad-leaved forest).
clc_312	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC312 (coniferous forest).
clc_313	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC313 (mixed forest).
clc_321	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC321 (natural grasslands).
clc_322	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC112 (moors and heathland).
clc_323	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC323 (sclerophyllous vegetation).
clc_324	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC324 (transitional woodland-shrub).
clc_331	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC331 (beaches, dunes, sands).
clc_332	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC332 (bare rocks).
clc_333	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC333 (sparsely vegetated areas).
clc_334	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC334 (burnt areas).

clc_335	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC335 (glaciers and perpetual snow).
clc_411	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC411 (inland marshes).
clc_412	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC412 (peat bogs).
clc_421	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC421 (salt marshes)
clc_422	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC422 (salines).
clc_423	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC323 (intertidal flats).
clc_511	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC511 (water courses).
clc_512	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC512 (water bodies).
clc_521	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC521 (coastal lagoons).
clc_522	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC522 (estuaries).
clc_523	boolean	Boolean flag indicating whether at least one sampled point within the area is classified as class CLC523 (sea and oceans).
clc_artificial_note	string	List of descriptive elements related to artificial land cover features present in the wetland area *(e.g., unpaved road, rural building, old mill)*
clc_agri_note	string	List of descriptive elements related to agricultural land cover features present in the wetland area *(e.g., arable land, permanent crops, orchard).*
clc_veg_note	string	List of macro-species related to natural and semi-natural vegetation land cover features present in the wetland area (*e.g., Populus, Carex, Iris*)
clc_wetlands_note	string	List of species related to wetland-specific land cover features present in the wetland area (*e.g., Phragmites, Sorghium*).
clc_water_note	string	List of descriptive elements related to water-related land cover features present in the wetland area (*e.g., aquaculture pond, fishing pond*).

Another relevant feature was the generation of standardized field assessment reports integrating cartographic products and structured textual descriptions. These outputs improved comparability among sites and supported interpretation by analysts and epidemiologists. An example of the report is presented in Figure 4.

Site 01- Nogara





Site description

Site 01 is located in the municipality of Nogara and covers a total area of 29,029.19 m², with a perimeter of 648.23 m.

It is a spring-fed area that has been restored and is publicly owned. The site is not protected or fenced. Access to the site is located immediately adjacent to the provincial road.

The shoreline vegetation reaches a height ranging between 0.5 m and 2 m. Bank slopes vary from gentle to steep. No islands or defecation sites are present.

Field surveys indicate the following land-cover characteristics (ref. Corine Land Cover classes 2018):

- 112 (Discontinuous urban fabric), 121 (Industrial or commercial units), 122 (Road and rail networks and associated land): Presence of an old mill nearby and an unpaved road. The wetland is located close to an industrial area.
- 212 (Non-irrigated arable land): Presence of managed agricultural surfaces.
- 311 (Broad-leaved forest), 313 (Mixed forest), and 321 (Natural grasslands): Vegetation includes a poplar grove and riparian forest formations.
- 411 (Inland marshes): Presence of helophytic vegetation such as Phragmites and Sorghum.
- 511 (Water courses): The water body is connected to a watercourse.

A hunting ban is in force in the area, but fishing activities are practiced. Human activity is low. Observed avifauna includes several individuals of pheasant and cormorant, as well as one dead individual of mallard (Anas platyrhynchos).



Overview of the wetland and the old mill structure (top left); panoramic view of the water feature and riparian vegetation, with a poplar grove in the background (top right); close-up of the riparian vegetation (bottom left); detail of water turbidity, with the industrial area visible in the background (bottom right).

Fig. 4 Example of a field assessment report for Site 01. The first page presents maps depicting environmental conditions and sample locations, while the subsequent page provides a detailed description of the site. Photographs were included where available. The original report was produced in Italian and translated into English for the purposes of this publication.

In addition, field validation activities identified discrepancies between existing local and satellite-derived environmental conditions, demonstrating the added value of in-situ GIS characterization for improving ecological realism. Direct field surveys revealed discrepancies between the actual configuration of water bodies and land cover in Sites 01, 05, 09, 02, and 08 were subjected to topological editing. For example, at Site 05, polygons were merged after it was determined that a presumed separating isthmus was in fact a permeable reed bed.

Discussions

The development of environmental surveillance strategies for AIVs, capable of complementing existing animal-based surveillance, is still in its infancy and current experience is mostly limited to pilot studies based on opportunistic sampling, with limited or no information on the environment characteristics of the sampling sites. To be effective, the design of risk-based sampling schemes for environmental surveillance requires dedicated tools that integrate geographic information, advanced data management, and informatics-based analytical capabilities. Such a transition demands a fundamental paradigm shift, as moving from individual bird-based to environment-based analysis means that the subject of investigation is no longer the animal itself, but the environment it inhabits. Consequently, the environmental context must be rigorously described in terms of ecological configuration, land use, hydrological features, and degree of human influence at the time of sampling. This is particularly important in the contemporary context of climate change and anthropogenic landscape transformation, which are driving rapid, often unpredictable shifts in environmental conditions that directly influence disease dynamics, as demonstrated by Shenglai et al. (2025) [46], who observed how landscape modification can substantially reshape waterfowl migration and increase the risk of wild bird-poultry spillover events. Such changes also create the conditions for emerging diseases to establish and spread into geographic areas that were previously free, making the precise environmental characterization of surveilled sites not just useful, but essential [47]. In this context, the proposed method operationalizes the One Health approach by enabling the systematic integration of environmental information with traditional epidemiological surveillance data. Beyond their immediate utility for epidemiological analyses, structured environmental datasets are becoming increasingly important as emerging infectious diseases continue to increase in frequency and unpredictability. Ongoing processes such as climate change, land-use transformation, biodiversity loss, and other forms of anthropogenic environmental disruption are altering ecological systems in ways that can modify host distributions, pathogen persistence, and transmission dynamics. In this context, surveillance strategies based exclusively on animal or pathogen-centered approaches may no longer be sufficient. Integrating detailed environmental and territorial information into surveillance frameworks will be increasingly necessary to better understand where, how, and under which ecological conditions diseases emerge, circulate, and spread.

The framework presented in this study demonstrates how a GIS-based workflow can support the standardization of environmental and territorial data collection during field surveillance activities. By integrating mobile GIS applications, centralized spatial infrastructures, and relational databases, the approach ensured that field observations were collected using harmonized attribute schemas and consistent spatial references. This is particularly relevant in environmental surveillance contexts, where observations are often heterogeneous, partially descriptive, and difficult to integrate into analytical processes. The use of predefined forms, conditional logic, and standardized identifiers reduced variability among operators and improved consistency across repeated field campaigns.

Raw environmental observations, which are typically fragmented across multiple records and field notes, were transformed into aggregated wetland-level descriptors suitable for epidemiological analyses. This process simplified downstream analytical activities by generating analysis-ready spatial covariates that could be directly integrated with laboratory outcomes and surveillance data. The implementation of database views and automated aggregation procedures also reduced the need for repeated manual data processing, improving reproducibility and minimizing the risk of transcription or interpretation errors.

The combination of GIS tools allows the identification and resolution of spatial inconsistencies during the early phases of the surveillance process, before final analytical stages. Real-time synchronization between field devices and the online GIS environment enabled immediate verification of collected data and facilitated rapid correction of topological or classification errors. In several wetlands, field observations

revealed discrepancies between existing geospatial datasets and actual environmental conditions. Within this validation framework, these discrepancies triggered spatial corrections, including manual digitization of missing or unrepresented water bodies, modification of polygon geometries to better reflect observed wetland morphology, and reinterpretation of land cover classes where misclassification was evident. These interventions were applied directly during data acquisition rather than post processing, thereby ensuring immediate dataset accuracy and consistency and reducing delays associated with later analytical corrections.

Furthermore, this validation process also supported comparison between field-observed land cover and pre-existing European Environment Agency (EEA)/CLC datasets, allowing refinement of environmental characterization. The comparison between field observations and publicly available environmental datasets, particularly Corine Land Cover and OpenStreetMap, further highlighted the limitations of relying exclusively on remotely derived or generalized land cover products for micro-scale epidemiological investigations. Several environmental features observed *in situ* differed substantially from their representation in existing datasets, especially in highly dynamic wetland environments characterized by vegetation changes, fluctuating hydrological conditions, and anthropogenic modifications. These findings underline the importance of integrating direct field-based validation into environmental surveillance workflows, particularly when ecological characteristics are expected to influence pathogen persistence or host distribution. This aspect is particularly relevant in the context of "GLOCAL" concept within the One Health framework [48], which recognizes that although the drivers of health risks often operate at global or regional scales, the processes through which they translate into disease emergence and transmission are shaped by local ecological and environmental conditions. The present study reflects this perspective by focusing on a geographically well-defined area and characterizing landscape features at high spatial resolution, thereby enabling a detailed survey of the local habitat that may influence pathogen transmission. This local perspective is essential as EIDs emerge from interactions among wildlife, livestock, humans, and their shared environments. At the same time, the global distribution of these events is influenced by broader socio-ecological drivers, including land-use change, population density, and biodiversity gradients [49]. Rather than representing alternative perspectives, local and global-scale processes should be integrated into a coherent analytical framework to better understand EID dynamics across scales.

More broadly, the study highlights the added value of GIS-based environmental characterization compared with purely descriptive field approaches. Rather than limiting environmental observations to qualitative annotations, the proposed framework transformed them into spatially explicit and standardized variables that can support reproducible and comparable epidemiological analyses. The integration of spatial databases, geofencing systems, and harmonized digital forms allowed environmental information to become part of a structured analytical infrastructure rather than supplementary descriptive material. This transition is particularly important within One Health surveillance systems, where environmental context increasingly represents a key component for interpreting disease dynamics.

Although the framework was specifically designed for avian influenza environmental surveillance in wetlands of north-eastern Italy, its methodological structure is sufficiently flexible to support other surveillance and ecological monitoring contexts. The approach provides a transferable methodological model for integrating field ecology, geospatial infrastructures, and epidemiological analysis in a broader range of One Health applications.

Conclusions

The GIS-based framework developed in this study provides a practical approach to address a critical gap in One Health environmental surveillance by standardizing the acquisition, harmonization, and management of fine-scale ecological data at HPAI sampling sites. The combination of user-friendly mobile forms with GIS tools (ESRI Field Maps), a cloud-based spatial infrastructure (ArcGIS Online), and relational spatial databases (PostGIS), within a standardized workflow ensures that collected data maintains full consistency from the initial field sampling up to the assessment report.

From a critical perspective, while satellite-derived and broad-scale environmental datasets offer valuable regional coverage, they frequently fail to capture the local heterogeneity, such as micro-habitat features;

precise shoreline morphology or, more generally, soil coverage in some specific points, all factors that could directly influence host aggregation and pathogen persistence. Ground-truthing and standardized field characterization have proven to be essential to correct spatial discrepancies in existing datasets, thereby preventing potential biases in subsequent epidemiological models.

The current implementation employs specific commercial and proprietary tools, these technologies are not intrinsic to the framework itself. The framework is technology-agnostic and can be implemented using different software solutions, provided that they support the required functionalities and interoperability standards. Consequently, future implementations could be fully migrated to an open-source ecosystem, reducing operational costs, enhancing long-term sustainability, and facilitating adoption by institutions with limited financial resources.

In conclusion, this standardized spatial infrastructure transforms unstructured field observation into reliable, reproducible and analytical covariates, providing a scalable blueprint that enhances the epidemiological value of environmental sampling, ultimately supporting more robust disease risk assessment and targeted surveillance strategies for avian influenza and other emerging infectious disease.

List of abbreviations

AIV: Avian Influenza Virus
CLC: Corine Land Cover
DPPA: Densely Poultry Populated Area
EEA: European Environment Agency
EID: Emerging infectious diseases
GIS: Geographic Information System
GPS: Global Positioning System
HPAI: Highly Pathogenic Avian Influenza
ISTAT: National Institute of Statistics
IZSVE: Istituto Zooprofilattico Sperimentale delle Venezie
LIMS: Laboratory Information Management System
OSM: Open Street Map

Declarations

Ethics approval and consent to participate

Ethics approval was not required for this study because it did not involve human participants, human biological material, animal experimentation, or identifiable personal data. The analyses were performed using environmental geospatial datasets, Earth observation products, OpenStreetMap data, and avian influenza environmental surveillance data collected as part of routine monitoring and research activities.

Consent for publication

Not applicable.

Availability of data and materials

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request, subject to any legal or institutional restrictions. Publicly available datasets used in this study, including OpenStreetMap and Earth observation products, are available from their respective repositories. Any data and material developed for the GIS workflow can be made available upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Conceptualization: [Matteo Mazzucato], [Giacomo De Conti]; Methodology: [Matteo Mazzucato], [Giacomo De Conti], [Diletta Fornasiero], [Luca Martelli], [Rodrigo Macario]; Investigation: [Giacomo De Conti], [Luca Martelli]; Data curation and Formal analysis: [Matteo Mazzucato], [Giacomo De Conti]; Writing - original draft preparation: [Matteo Mazzucato], [Giacomo De Conti]; Writing - review and editing: [Matteo Mazzucato], [Giacomo De Conti], [Diletta

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