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Mapping Italian high-altitude ponds

Davide Taurozzi [1] · Massimiliano Scalici [1,2]

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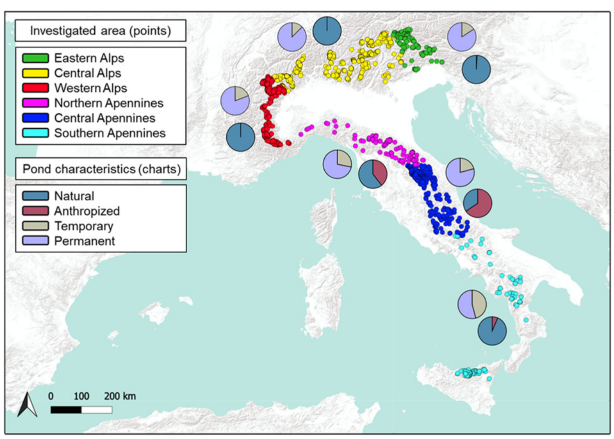
Abstract

Permanent and temporary ponds are considered peculiar ecosystems which provide important ecosystem functions, services, supporting biodiversity on small and large scales. Pond's conservation status is globally critical. Moreover, their ecological functioning and conservation status is frequently overlooked, because of the habitat small size, their seasonal occurrence and their unique appearance. While a certain attention is given to Mediterranean Temporary Ponds and, in general, to low altitude ponds, the ecological importance of high-altitude ponds is critically unrecognized, especially in the Italian peninsula. The main aim of this research is to create the first georeferenced checklist of Italian high-altitude ponds. In order to achieve this goal, we integrated spectral, spatial characteristics, and morphological operations based on Sentinel-1 and Sentinel-2 image data using the Google Earth Engine (GEE). Overall, 2156 ponds were identified: 62% ($n = 1343$) in the Alps and 38% ($n = 813$) in the Apennines. The highest number of ponds was detected in Central Alps ($n = 642$), followed by Western Alps ($n = 479$), Central Apennines ($n = 412$), Eastern Alps ($n = 222$), Southern Apennines ($n = 216$) and Northern Apennines ($n = 185$). For what concerns the Alps, the average altitude was estimated in 2428 m a.s.l., while in the Apennines the average altitude was estimated in 784 m a.s.l. The total area covered from ponds has been estimated in 4.258.640 m^2, with a mean of 1716 m^2. Ponds were described as 20% temporary ($n = 445$) and 80% permanent ($n = 1711$). Considering the land use, 83% ($n = 1797$) of ponds were described as "natural" and 17% ($n = 359$) as "anthropized". Identification and georeferentiation of high-altitude ponds are primary actions to the application of management plans and this research could be considered the first step towards the safeguard of these threatened ecosystems.

Graphical Abstract



Keywords Temporary · Permanent · Conservation · Anthropized · Climate change · Natural

✉ Davide Taurozzi
davide.taurozzi@uniroma3.it

[1] Department of Sciences, University of Roma Tre, Rome, Italy

[2] National Biodiversity Future Center (NBFC), Università di Palermo, Palermo, Italy

Introduction

Ponds are generally described as small (<5 ha) water bodies which are shallow (<5 m depth), with less than 30% of

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emergent vegetation (Olmo et al., 2022; Richardson et al., 2022). However, following this definition, ponds could overlap with other types of waterbodies: for this reason, their exactly definition is still debated in scientific literature. For example, The CEN standard defined lakes as water bodies characterized by surface areas greater than 1 ha (0.01 km^2) and maximum depths (at mean water level) greater than 1 m (Boon et al., 2019). Given the variety about those definitions, we adopted in this research the most recent and functional definition to distinguish ponds from lakes and wetlands from Richardson et al. (2022). Anyway, ponds are the most numerous freshwater environments globally (Biggs et al., 2017) and are considered peculiar ecosystems which provide important ecosystem functions (e.g., stepping stones) and services (e.g., nutrient retention, hydrological regulation) (Coccia et al., 2024). Ponds are not isolated systems. They are strongly linked to other aquatic systems and their surrounding terrestrial environment (Fehlinger et al., 2023). Temporary ponds (also known as vernal pools or ephemeral pools) are seasonally flooded aquatic habitats that support unique assemblages of fauna and flora (Taurozzi et al., 2024; Fritz and Whiles 2021). The term "temporary" refers to the hydroperiod of these ecosystems (i.e., the length of aquatic phase) (Fernández-Zamudio et al., 2016). Temporary ponds are characterized by a dry phase which occur, regularly, during spring and summer, when temperatures and scarce precipitations can reduce partially or totally the water supply (Boix et al., 2016). However, if anthropogenic disturbances like climate change occur, this natural cycle could shift, generating irregularities in hydroperiod length and water quantity (Celewicz and Gołdyn, 2021). Differently, permanent ponds are characterized by the presence of water throughout the year, without suffering a dry phase in the summer season (Obrador et al., 2018). Both temporary and permanent ponds are recognized as biodiversity hotspots, characterized by unique chemical, biological and physical features: these give them a crucial role in biodiversity conservation (Obrador et al., 2018; Bagella et al., 2016; Hassall, 2014).

The conservation status of ponds is globally critical (Bolpagni et al., 2019; Hill et al., 2018). Although the increasing awareness of temporary ponds in terms of ecosystem services and support to freshwater and terrestrial biota, their ecological functioning and conservation status is frequently overlooked (Oertli et al., 2010), because of the habitat small size, its seasonal occurrence and its unique appearance (Van den Broeck et al., 2015: Céréghino et al., 2010). In Europe, a particular conservation status is provided for the "Mediterranean Temporary Ponds": the European Community, recognizing the value of these environments, referred them to the priority habitat 3170*, listed in Annex I of the Habitat Directive (92/43/EEC) (Bagella, 2023). Near this habitat, there is a wide range of habitats, all characterized by permanent or temporary existence. The Habitats Directive focuses on the conservation of some target species and vegetation types, using their presence to categorize a pond into one of the habitats included in the Directive (e.g., *Littorelletalia uniflorae*, *Isoëtes spp*., *Chara spp*.) (Campagnaro et al., 2018). In this way, it leaves out numerous ponds that do not show the presence of target species, vegetations type or habitats, but which represent the same, however, a fundamental ecosystem to preserve. In our study we will evaluate the effectiveness of Habitat Directive and National network of protected areas in the conservation of high-altitude ponds.

In fact, while a certain attention is given to Mediterranean Temporary Ponds and, in general, to low altitude ponds, the ecological importance of mountainous small waterbodies is critically unrecognized (Wissinger et al., 2016; Ilg and Oertli, 2014). Among all types of lentic waters, high-altitude ponds seem to be one of the most sensitive to climate change (Rosset et al., 2010). They are usually shallow, small, and temporary aquatic ecosystems located at an altitude above 300 m a.s.l., with a dry period recurring in late summer every year and lasting until the next year snow melting (Lamouille-Hébert et al., 2024; Wissinger et al., 2016). These ecosystems can show a double "dry" phase: the first during late summer, when water evaporates due to the high temperatures; the second during winter, when snow and cold temperatures make many of these ponds frozen or, in any case, without water reserves immediately available (Harrison-Day et al., 2019; Salerno et al., 2014). For this reason, high-altitude ponds show a wet phase restricted to few weeks, generally from early spring to early summer (Wissinger et al., 2016). To date, high-altitude ponds are considered biodiversity hotspots and, although these aquatic ecosystems represent a small part of the mountain region, they are a key component in safeguarding aquatic biodiversity (Blanco et al., 2020).

The Italian peninsula is largely characterized from both flat and hilly habitats and mountainous ecosystems. The Alps and the Apennines represent the two main mountain ranges. At the same time, the Italian peninsula is characterized by a large distribution of temporary and permanent ponds (Della Bella et al., 2007; Bazzanti et al., 2003), actually overlooked. In particular, high-altitude ponds in Italy show low concern and their distribution represent an important lack of knowledge, considering also that these lentic environments can represent key habitats for biodiversity conservation (Carchini et al., 2005). Some important questions to solve can be synthesized in:

– How many high-altitude ponds are present in Italy?
– Where are high-altitude ponds mostly distributed in Italy?

- How many of them can be considered natural and how many of them show anthropogenic origin?
- Are there more temporary or permanent ponds?

Mapping the distribution of high-altitude ponds is crucial for managing their dwindling quantities and quality (Malahlela, 2016). The geographical distribution of high-altitude ponds, considered a starting point for management plans, is often overlooked, because the low attention given to these ecosystems and the relative difficulty to identify their distribution. Moreover, it is considered particularly challenging to inventory these water bodies as they are generally small, numerous, temporary, and spread over large and often poorly accessible areas (Soti et al., 2009). The temporary hydroperiod and the restricted time available for the presence of water render the process, in some cases, even more difficult. Mapping natural resources like forests and water bodies using satellite image data have increased much importance and significance in the last decades (Wondrade et al., 2014). Data acquired by Satellite systems, covering a wide range of spectral, spatial, and temporal features, can be used for inventorying and monitoring high-altitude ponds and locating them over large areas (Soti et al., 2009; Ozesmi and Bauer, 2002).

The Italian peninsula currently lacks a checklist of high-altitude ponds. This could represent an important gap for conservation activities of these extremely threatened ecosystems. Identification and georeferentiation of high-altitude ponds are fundamental data to make a first step towards the application of management plans and the safeguard of these lentic ecosystems. The main aim of this research is to create the first georeferenced checklist of Italian high-altitude ponds. Given the numerous anthropogenic impacts which could impact ponds hydroperiod, in particular climate change (Lamouille-Hébert et al., 2024), we hypothesize that permanent and natural ponds show a larger distribution compared to temporary and anthropogenic ones. To achieve this goal, we integrated spectral, spatial characteristics, and morphological operations based on Copernicus Sentinel-1 and Copernicus Sentinel-2 image data using the Google Earth Engine (GEE) platform to develop a quick method for mapping high-altitude ponds in the Italian peninsula, providing information about geographical and altitudinal distribution and morphological features.

Materials and methods

Study area

The study focused on the Italian Peninsula, considering the two main mountain ranges: the Alps and the Apennines. The Alps and the Apennines represent part of a continuous Alpine orogenic system derived from a complex space-time interaction between the two major European and African plates (Molli et al., 2010). The political boundaries of the mountain ranges were taken from the European Soil Data Centre (Hiederer, 2013). The Alps have been divided into Western, Central and Eastern Alps (Brückl et al., 2010) following the Partition of the Alps from Comitato Geografico Nazionale Italiano (1926), showing a fundamentally different geological structure, geomorphology, and geological development (Neubauer et al., 2000). The system adopted covered the entirety of the Alps and not just that part of the Alps that lay on Italian soil. In our research, only the Alps laying on Italian political boundaries were considered.

The Apennines are a mountain range stretching from southern Piedmont to northern Calabria and Sicily with a total length of more 1000 km and a maximum width of 80/140 km (Di Pietro, 2009). Conventionally, the Apennines are divided in Northern (Mirabella et al., 2011), Central (Carafa et al., 2020) and Southern Apennines (Dichicco et al., 2019). Similarly to the Alps, generated from subduction of Europe “eastward–southeastward” underneath the Adriatic plate, the Apennines were generated by the “westward” subduction of the Adriatic plate (Carminati and Doglioni, 2012).

Geomorphological and hydrological features represent important environmental drivers influencing the composition of aquatic flora and fauna of ponds (Florencio et al., 2014) and their hydroperiod length. The Italian Alps are characterized mainly by crystalline magmatic rocks and carbonate platforms; the Apennines shows a soil system made of flysch and marly-arenaceous turbiditic facies on its northern side and carbonate and calcareous units in its central and southern sides (Bini, 2013). However, in this research, the division of the Alps and the Apennines in six zones follow the conventional partition adopted in literature; this partition was adopted instead to help the readers to clearly understand the results obtained. In this case, geomorphological characteristics will not be considered and discussed.

Data collection

Mountains are rugged structures in the landscape that are difficult to outline; whether an area belongs to mountains or not is a matter of definition and has substantial conservational and biogeographic implications (Körner et al., 2021). In our research, we adopted the mountain delineation by Kapos et al. (2000). This approach was developed for the United Nations Environmental Program (UNEP) through their World Conservation Monitoring Centre (WCMC). Following this approach, all lands with 300 m elevation above sea level (a.s.l.) are included in mountainous ecosystems. Given the necessity to standardize the research, our study was restricted to ponds located at a minimum altitude of 300 m a.s.l. (Körner et al., 2021; Körner et al., 2017).

Data collection was performed with the adoption of the satellite images of Copernicus Sentinel-1 and Copernicus Sentinel-2, used to extract ponds area, perimeter, altitude and the relative coordinates of the ponds (Chitiga, 2018; Ogilvie et al., 2020). Sentinel-2 carries an optical instrument payload that samples 13 spectral bands: four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution (Drusch et al., 2012). The orbital swath width is 290 km. The choice to use Sentinel satellites rather than Landsat ones, lies in the greater spatial (Sentinel = 10 m, Landsat = 30 m) and temporal (Sentinel = 5 days, Landsat = 16 days) resolution of the former (Phiri et al., 2020). Considering the small size and the short hydroperiod of some ponds, the Sentinel satellite has proven to be more effective in correctly identifying the site and calculating the spatial dimensions. Moreover, as described by Topaloğlu et al. (2016), image classification accuracies of Sentinel-2 are better than Landsat-8. In this work, we generated the referenced data by manual digitization of the presence and surface water with the assistance of Very High Resolution Satellite imagery from GEE (Google Developers, 2024) and ESRI World Imagery basemaps (ESRI, 2024). Accuracy (the distance between the actual geographic location of an object or detail compared to the position of the object in the image) and validation of the satellite images were also tested measuring points in situ with GPS following Topaloğlu et al. (2016) and then comparing them with satellite images from 16 ponds in the Apennines and 8 ponds in the Alps. Maximum Likelihood classification algorithm was used to classify Sentinel-1 and Sentinel-2 images. Overall accuracy of Sentinel-1 and Sentinel-2 images for water was estimated in 97%, in accordance with Topaloğlu et al. (2016).

We limited our area of interest within latitude 47°30’N–38°00’N and longitude 6°30’E–17°00’E. Data collection was performed with a standard virtual eye altitude of 300 m from GEE. Visualization, identification and references of ponds were performed moving along an S-shaped line inside the field of view from top to bottom, then moving from left to right to do not overlap with the previous field of view and then proceeding in the opposite direction. Geographical coordinates, altitude and the estimated area and perimeter of the ponds were recorded using the ”surface calculator” tool from GEE. A unique code was then assigned to each pond, made up of two letters which indicates the partition of the Alps considered (WA = Western Alps; CA = Central Alps; EA = Eastern Alps) and a consecutive number; regarding the Apennines, the code was built with three letters (NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines) followed by a consecutive number. Considering the historical image database provided from GEE, and to avoid the impact of pond drainage on the extraction effect, we selected the images from the most recent winter season (December 2023–February 2024) for the lower ponds (not subject to snow cover), when available, to search for ponds and estimate their surface area. On the contrary, for the very high-altitude ponds, which go frozen in winter, we selected images from the most recent late spring and early summer seasons (April–June 2023). In addition, we selected images with the lowest cloud coverage in the study area during the timeframe. For those ponds which are not covered by snow, winter is considered the season when the pond water supply is at its maximum (Hayashi and van der Kamp, 2021). Instead, for high-altitude ponds which go frozen during winter, the maximum level of the water is generally reached at the beginning of the summer (Thielke et al., 2023; Anhaus et al., 2021). Then, we collected all the images from the previous years (back to 15 years) to distinguish between “Temporary” and “Permanent” nature of the ponds. This approach also allows us to avoid errors in the assessment of the actual existence of ponds, which can otherwise be confused with shadow areas or geological features. The analysis of historical series therefore provides a validation of the method of identification of the pools through satellite data. To distinguish between temporary and permanent, we analysed images available from the summer season (June–August), considered, at these latitudes, the “dry” period. Ponds with at least one image where they appear dry, were considered as “temporary”. High-altitude ponds can be identified and distinguished from other artificial or natural water bodies (such as lakes, reservoirs) with radar satellite data on the basis of different edges (not precise geometric shape) in combination with size, vegetation cover and shape features. Finally, all the water bodies identified with GEE labels as “lake”, “lagoon” were excluded from the research. Following this criterion, some examples of excluded ponds are shown in Fig. S1. The land use was determined by CORINE Land Cover (CLC, 2018), a standardized methodology for producing continent-scale land cover, biotope, and air quality maps. Two land cover classes were considered: “Natural” and “Anthropized”. Each pond was assigned to one class or another considering the high percentage of land cover in a buffer zone of 300 m: if at least 51% of the land cover was a natural habitat, the pond was considered as “natural”. The same criterion was adopted for the “anthropized” classification, considering human activities (including agriculture and livestock) (Fig. 1). This division was adopted to simplify the ponds classification and make the results easier to interpret for the readers.

Results

The development of a method based on GEE enabled us to elucidate the national-scale pond distribution in the Alps and the Apennines of the Italian peninsula using Copernicus

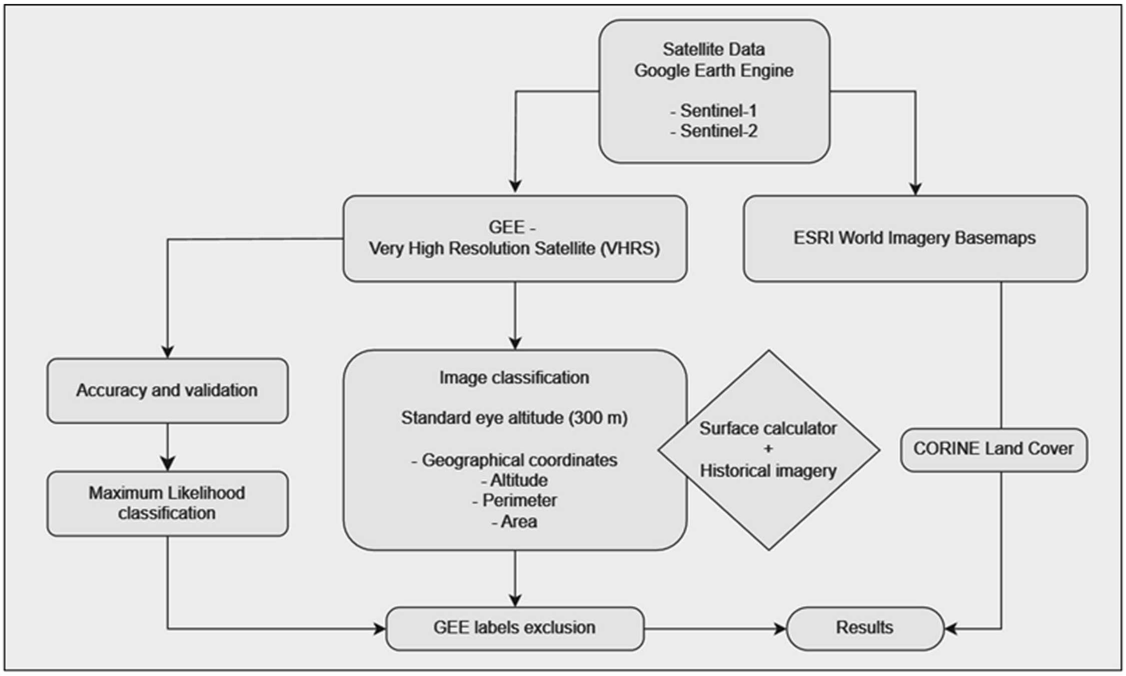

Fig. 1 The flowchart of the methodology

Sentinel-1 and Copernicus Sentinel-2. The results provide a comprehensive overview of the spatial distribution of ponds in the principal Italian mountain ranges. The total area of the Alps and the Apennines was estimated in 109.180 km^2. Overall, 2156 ponds were identified: 62% ($n = 1343$) in the Alps and 38% ($n = 813$) in the Apennines. The highest number of ponds was detected in Central Alps ($n = 642$), followed by Western Alps ($n = 479$), Central Apennines ($n = 412$), Eastern Alps ($n = 222$), Southern Apennines ($n = 216$) and Northern Apennines ($n = 185$) (Fig. 2).

In 2024, the total area covered from ponds was estimated in 4.258.640 m^2, with a mean of 1716 m^2, and the relative coverage of the ponds was 0.004% of the total surface of the Alps and the Apennines. Overall, the highest area covered by ponds was reported for CA (37%), followed by WA (23%), CAP (23%), EA (7%), NAP (5%) and SAP (4%) (Fig. 3). The largest area was recorded in EA (37091 m^2), while the smallest area was recorded in CAP (5.50 m^2).

The total perimeter of ponds was estimated in 333.279 m, with a mean of 140 m. Overall, the highest perimeter covered by ponds was recorded for CA (34%), followed by WA (24%), CAP (21%), EA (8%), NAP (6%) and SAP (6%). The largest perimeter was recorded in CA (1799 m), while the smallest perimeter was recorded in CAP (9.46 m) (Fig. 3).

Overall, 42% ($n = 909$) of ponds are actually included in almost one Natura 2000 site, Special Area of Conservation (SAC), Site of Community Importance (SCI), Special Protection Site (SPA), Regional or National Park. In particular, WA shows the highest percentage of "protected" ponds with 62% ($n = 301$), included in almost one European Union or National protected area, followed by EA (48%, $n = 106$), SAP (44%, $n = 95$), CA (38%, $n = 243$), NAP (31%, $n = 57$), CAP (26%, $n = 107$).

For what concerns altitude, the highest value was recorded in WA (3345 m a.s.l.), while the lowest were recorded in NAP and CAP (300 m a.s.l.). Overall, the Alps show the highest altitude values, with the lowest value recorded at 693 m a.s.l. (EA). Regarding the Apennines, the highest altitude value was recorded in CAP (2048 m a.s.l.). The average altitude was estimated in 1577 m a.s.l. Regarding Alps, the average altitude was estimated in 2428 m a.s.l., while in the Apennines the average altitude was estimated in 784 m a.s.l. WA shows the highest average altitude (2580 m a.s.l.) for the Alps, while EA shows the lowest (2109 m a.s.l.).SAP shows the highest average altitude (990 m a.s.l.) for the Apennines, while NAP shows the lowest (603 m a.s.l.) (Fig. 4).

The nature of ponds was described as 20% temporary ($n = 445$) and 80% permanent ($n = 1711$) regarding the hydroperiod. In particular, the highest number of permanent ponds was recorded in CA ($n = 561$), followed by WA ($n = 387$), CAP ($n = 326$), EA ($n = 187$), NAP ($n = 133$), SAP ($n = 117$). The highest number of temporary ponds was recorded in SAP ($n = 99$), followed by WA ($n = 92$), CAP ($n = 86$), CA ($n = 81$), NAP ($n = 52$), EA ($n = 35$).

Moreover, considering the land use, 83% ($n = 1797$) of ponds were described as "natural" and 17% ($n = 359$) as "anthropized". WA and CA show 100% of "natural" ponds, while EA shows 99% of "natural" ponds. CAP represents the only zone where "anthropized" ponds show higher

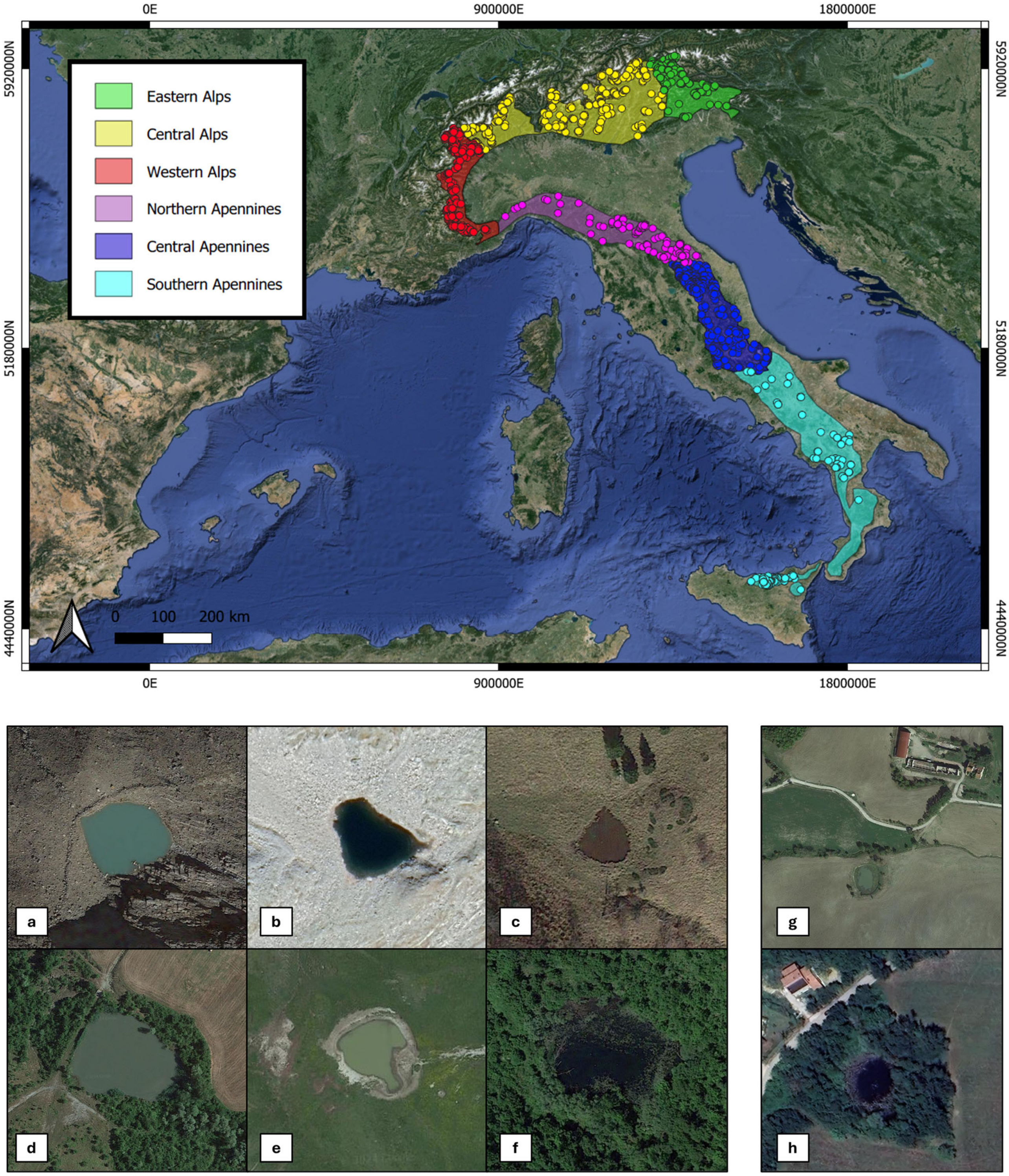

Fig. 2 Above: distribution of SW in the Italian Peninsula. The six zones considered are traced with different colors. Below: pictures of some different ponds detected (**a**–**f**: "Natural" ponds; **g**, **h**: "Anthropized" ponds). **a** WA91; (**b**) CA4; (**c**) EA98; (**d**) NAP56; (**e**) CAP37; (**f**) SAP19; (**g**) NAP61; (**h**) CAP271

abundances than "natural" ones. The highest number of "natural" ponds was recorded in CA ($n = 642$), followed by WA ($n = 479$), EA ($n = 220$), SAP ($n = 202$), CAP ($n = 142$) and NAP ($n = 112$). The highest number of "anthropized" ponds was recorded in CAP ($n = 270$), followed by NAP ($n = 73$), SAP ($n = 14$) and EA ($n = 2$) (Fig. 5).

Data of the ponds' areas were tested both for normality and homogeneity of variance. The ANOVA test calculated

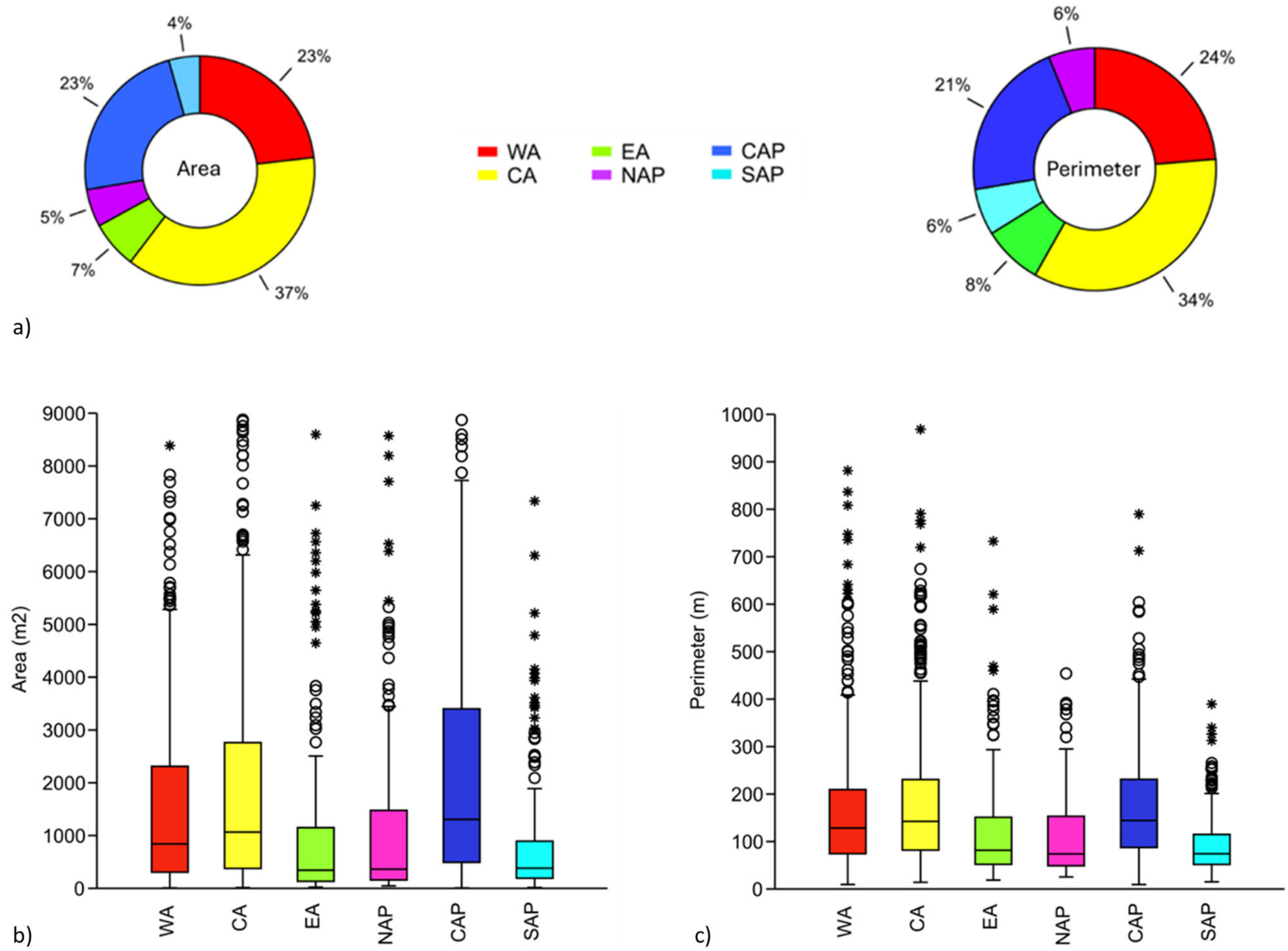

Fig. 3 **a** Total area and perimeter recorded for the six zones considered; (**b**) boxplot of ponds' area values; (**c**) boxplot of ponds' perimeter values. (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

for the ponds' areas shows significant differences between groups ($F = 12.99$, $p < 0.05$). Tukey post-hoc test highlights differences between groups shown in Table 1.

Ponds' altitudes data were tested both for normality and homogeneity of variance. The ANOVA test calculated for the ponds' altitudes shows significant differences between groups ($F = 2011$, $p < 0.05$). Tukey post-hoc test highlights differences between groups shown in Table 2.

Correlation between "Area" and "Perimeter" were tested for all the six cases. All the zones show high correlation between these two variables (WA, $r = 0.88$, $p < 0.05$; CA, $r = 0.82$, $p < 0.05$; EA, $r = 0.83$, $p < 0.05$; NAP, $r = 0.97$, $p < 0.05$; CAP, $r = 0.92$, $p < 0.05$; SAP, $r = 0.94$, $p < 0.05$).

Linear regressions were performed to evaluate correlations between variables "Area" and "Altitude" for the six zones. Area and altitude result low correlated in all the six zones considered: in particular, average low positive correlation trends emerge for the Alps while average low negative trends emerge for the Apennines (Fig. 6).

Contingence tables were created to evaluate the relationship between the variables "Area", "Altitude", "Land cover" and "Hydroperiod" for the six zones considered.

Chi-squared tests were performed grouping altitudinal and area data in four classes (or quartiles, chosen in function of the altitudinal and area values of each zone). The results were shown in Table S1. Chi-squared tests show: (i) medium dependence between hydroperiod and land use ($V = 0.33$) and low dependences between altitude and land use ($V = 0.25$) and area and land use ($V = 0.27$) for NAP; (ii) strong dependences between altitude and hydroperiod ($V = 0.56$) and altitude and land use ($V = 0.72$), medium dependence between hydroperiod and land use ($V = 0.49$) and low dependence between area and hydroperiod ($V = 0.19$) for CAP; (iii) medium dependence between altitude and hydroperiod ($V = 0.33$) and between altitude and land use ($V = 0.30$) and low dependence between area and hydroperiod ($V = 0.26$) and between area and land use ($V = 0.26$) for SAP (Fig. 7).

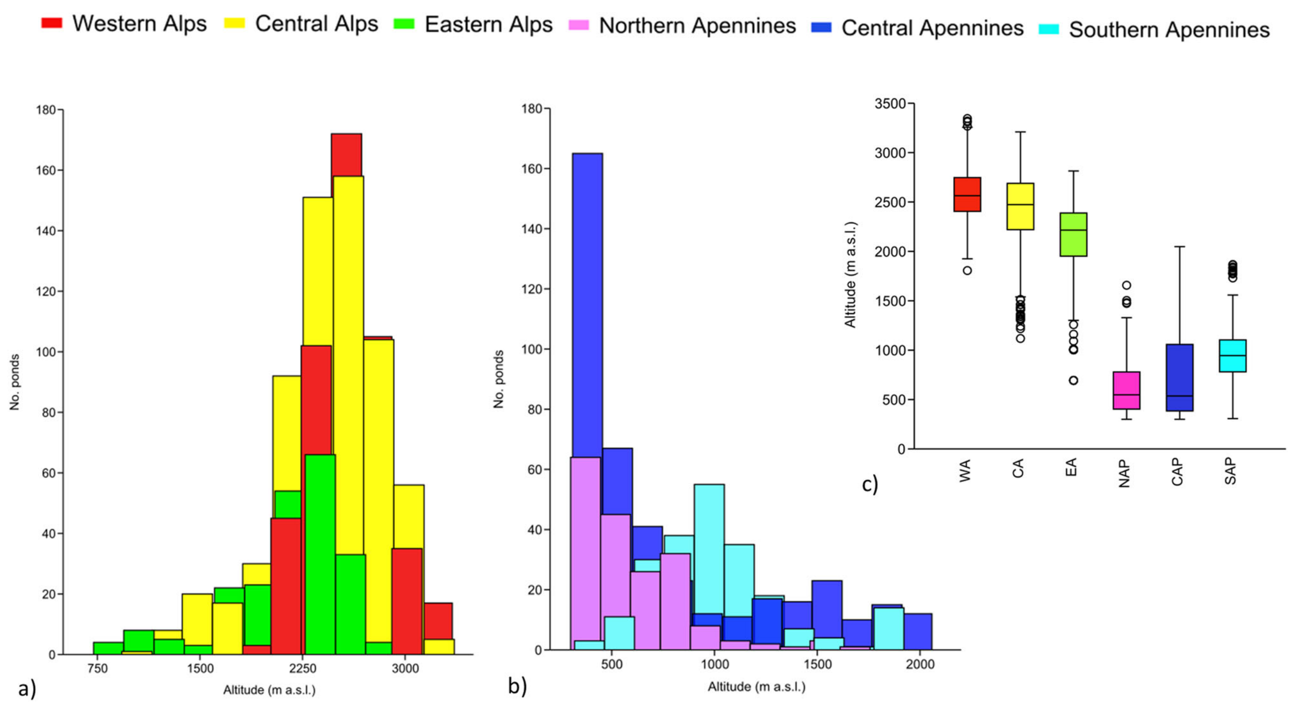

Fig. 4 **a** Barchart of altitude values of ponds in the Alps; (**b**) barchart of altitude values of ponds in the Apennines; (**c**) boxplot of mean altitudes recorded (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

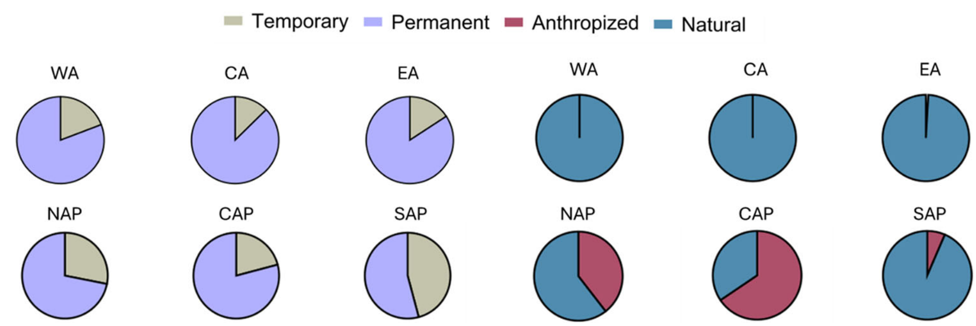

Fig. 5 Piecharts of the land use and hydroperiod of the six zones considered (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

Table 1 Tukey's Q (below the diagonal) and p (same, above the diagonal) for area values; significant comparisons are bold (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

	WA	CA	EA	NAP	CAP	SAP
WA		0.3392	**0.04478**	**0.04192**	0.6205	**0.0001471**
CA	2.837		**7.533E-05**	**0.0001175**	0.9999	**1.384E-08**
EA	4.089	6.463		1	**0.0006525**	0.7634
NAP	4.121	6.328	0.2489		**0.0007842**	0.8806
CAP	2.216	0.3541	5.776	5.713		**4.263E-07**
SAP	6.258	8.698	1.893	1.559	7.878	

Discussions

This study focused on the extraction of Italian high-altitude ponds from Copernicus Sentinel-1 and Copernicus Sentinel-2 images. Some small-scale ponds constitute the mixed pixels in the 30-m spatial resolution satellite images (Duan et al., 2020), thus, it is difficult to extract individual ponds, evaluate their precise area and perimeter while excluding clearings between them. Moreover, for the first time, the Italian Alps and the Apennines regions were taken into consideration in this study, and this consideration is consistent with the distribution of high-altitude ponds in the Italian peninsula and their underrated value. However, as high-altitude ponds represent a specific ecosystem,

Table 2 Tukey's Q (below the diagonal) and p (same, above the diagonal) for altitude values; significant differences are bold (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

	WA	CA	EA	NAP	CAP	SAP
WA		**2,748E-10**	**6,415E-11**	**6,415E-11**	**6,415E-11**	**6,415E-11**
CA	9,609		**6,42E-11**	**6,415E-11**	**6,415E-11**	**6,415E-11**
EA	21,85	15,33		**6,415E-11**	**6,415E-11**	**6,415E-11**
NAP	85,97	82,23	56,94		**5,84E-05**	**6,421E-11**
CAP	102,1	99,53	61,13	6,54		**6,721E-11**
SAP	73,02	68,71	44,06	14,55	10,46	

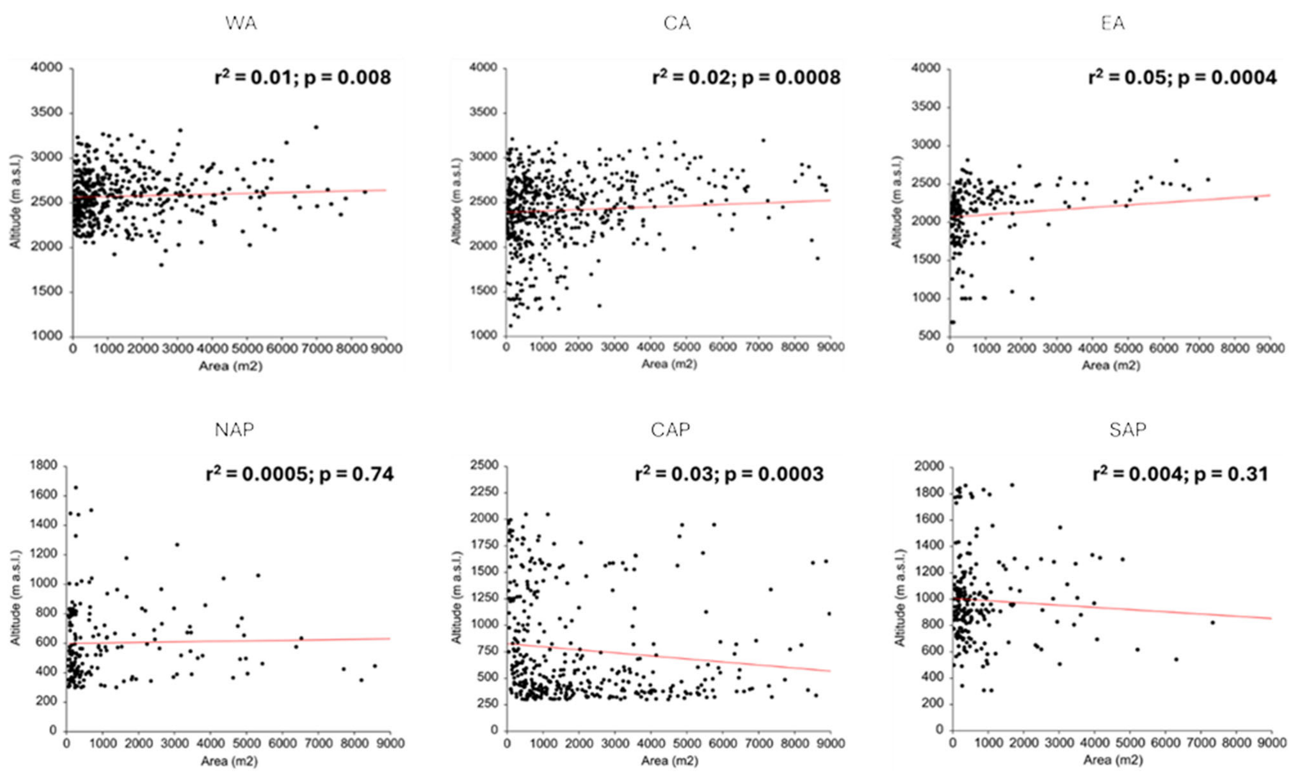

Fig. 6 Least square regressions for the variables "Area" and "Altitude". (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

including several different small waterbody types (Taurozzi et al., 2024), it is difficult for traditional classification methods or a single spectral index to efficiently identify and classify high-altitude ponds at a large scale (Şerban et al., 2020). Therefore, we developed a method based on Copernicus Sentinel-1 and Copernicus Sentinel-2 images to enable the extraction of the whole high-altitude ponds on a national scale by combining spatial features, historical imagery, and morphological characteristics.

The Copernicus Sentinel satellite missions offer free access to continuous, timely, and routine Earth observation data (Jutz and Milagro-Perez, 2020) and thus offer enormous potential for large-scale and even national assessment of high-altitude ponds (Ottinger et al., 2021). Our research demonstrated the possibility to detect and map high-altitude ponds at the single-pond level for a national scale combining available data of essential time series information derived from high-spatial-resolution Sentinel-1 radar imagery in combination with Sentinel-2 optical time series information, as well as topographical and geometric features.

Overall, the highest number of ponds detected was in the Alps. This heterogeneous distribution can be related to the scarce tree coverage located on the Alps rather than Apennines. Leonelli et al. (2011) estimated the tree line for the Italian Alps at an altitude of about 2500 m a.s.l. 46% of the high-altitude ponds were detected above this altitude. In the last three centuries, the Italian Alps were extensively used for agriculture (Monzani, 2021; Chemini and Rizzoli, 2003), with many forests cleared for meadows and pastures (Tasser et al., 2007). Furthermore, grazing in subalpine forests created forest pastures with sparse tree coverage

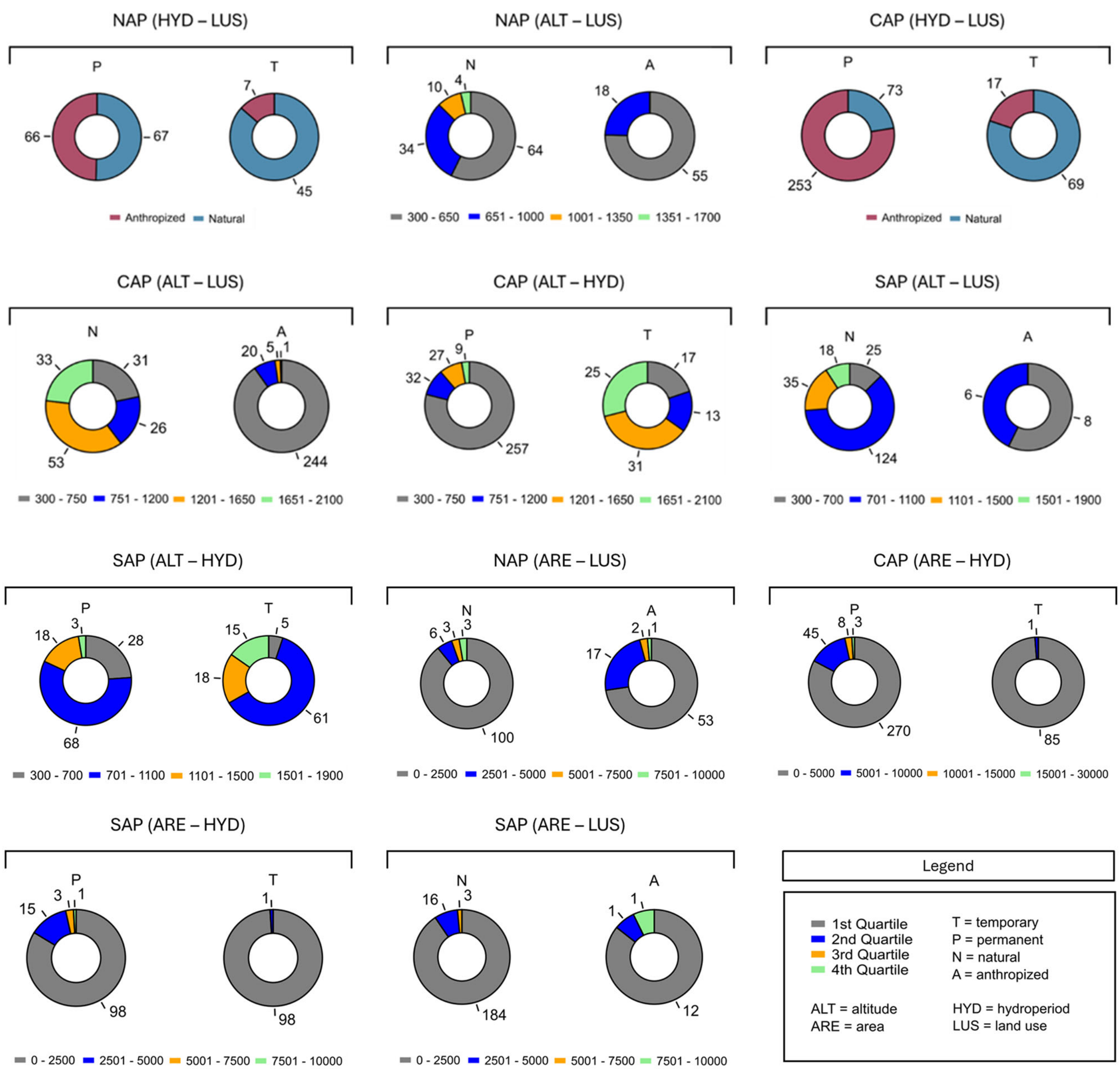

Fig. 7 Pie charts of the significant ($p < 0.05$) dependences calculated with chi-squared tests. The zone considered and the relative variables investigated are presented above each couple of pie chart. Label numbers represent the values emerged from dependence analysis. The variables considered are shown in the "Legend" box. Values below the pie charts represent the values of altitude (ALT) and area (ARE) found and organized in quartiles. (WA = Western Alps; CA = Central Alps; EA = Eastern Alps; NAP = Northern Apennines; CAP = Central Apennines; SAP = Southern Apennines)

(Stritih et al., 2023). On the contrary, the Apennines show a lower average altitude (Carminati et al., 2004), often below the tree line. These results translate into difficulties in identifying ponds in some cases using satellite images, due to the tree coverage. A widespread tree cover can be considered the limit of our research. In such cases, the only way to track down ponds is to do on-site inspections (Mahmoud et al., 2023). Indeed, as suggested by Boardman (2016), Google Earth is ideal for reconnaissance mapping and the discovery of sites missed during field work. The use of Google Earth "historical imagery" tool could provide an important help for detect ponds where an extensive tree coverage is present (Li et al., 2023; Duan et al., 2020). In the Anthropocene Era, characterized by numerous human influences and threats on environment, a 10 or 15-year look back could reveal the presence or absence of many environmental elements, now disappeared (Smith and Zeder, 2013). Moreover, as reported by Leonelli et al. (2011), also treelines are mainly influenced by human impacts and by geomorphological factors. Historical imagery can reveal the existence of a pond where, nowadays, an extensive tree cover is present. However, to provide a complete overview of the pond distribution, only the most recent images from Copernicus Sentinel-1 and Copernicus Sentinel-2 satellites were considered in this study.

From the results emerges an estimated coverage of 0.004% of ponds respect to the total area under study. Considering the large portion of natural "pristine" environment available, especially on Italian Alps (Pastorino et al., 2024), and the critical status of conservation of ponds worldwide, this percentage represents an alarm bell for the conservation of these habitats. Although ponds represent a neglected habitat, scientific awareness about these ecosystems raised in the last years, in particular for Mediterranean temporary ponds (MTPs), considered as priority habitat (Bagella, 2023). However, in matters of legislation, the Habitats Directive (Council Directive 92/43/CEE) recognize only a small part of MTPs basing on the presence of target plant communities and excluding many other ponds, in particular high-altitude ponds; furthermore, the Water Framework Directive could represent an important tool for the protection of MTPs in Europe, but unfortunately the local legislation of many states fixed 50 ha as the minimum size of a waterbody for its application (Bagella et al., 2016). This limit emerges also from our research. We demonstrated that only 42% of ponds are included in, at least, one Natura 2000 site, Special Area of Conservation (SAC), Site of Community Importance (SCI), Special Protection Site (SPA), Regional or National Park. Natura 2000 network represents the most important conservation effort being implemented in Europe, increasing from 11% to 20% the area devoted to conservation in Italy and the coverage provided to areas with high biodiversity (Hermoso et al., 2019). However, as reported by Maiorano et al. (2007), if Natura 2000 is taken to represent the last point of all the EU conservation policies, it will inevitably fail. Given that Natura 2000 is not suitable alone for maintaining listed species and habitats in a "favorable conservation status" (Bastian, 2013; Maiorano et al., 2007), the high number of excluded ponds (58%) represent a critical situation for the conservation of these ecosystems. It is out of doubt that Natura 2000 represent, together with existing protected areas, an important component on which to build future conservation efforts. Nevertheless, further studies and management plans are necessary to expand the dimensions of protected areas to include and protect as many ponds as possible. Therefore, the data collected for monitoring water bodies at the European level cannot be used for the assessment of small ponds, as for other large water bodies (Bolpagni et al., 2017).

Data obtained acquire still more importance if related to ponds hydroperiod. The small percentage of temporary ponds detected (20%) suggest that, although the Alps show a dominance of permanent ponds, the Apennines, in particular SAP, are suffering a hydric crisis (Polemio and Casarano, 2008). Droughts and water shortage conditions, which occur frequently in southern Italian regions (Rossi and Peres, 2023; Buttafuoco et al., 2018; Mendicino et al., 2008), can affect ponds hydroperiod, favoring temporary ponds over than permanent ones. High-altitude ponds, although being characterized by a restricted dry phase (both for winter snow and summer drought), showed a predominantly permanent nature: these results can be addressed to the lower temperatures characterizing high altitudes. Temperature, precipitation, and evaporation rate represent the main factors influencing pond hydroperiods (Hayashi and van der Kamp, 2021; Florencio et al., 2020).

Moreover, as reported by Acquaotta et al. (2015), WA showed, in the last 20 years, an increase in temperature, particularly at high-altitudes sites (>2600 m a.s.l., Fahy et al., 2024), and a decrease in the number of cold periods due to anthropogenic climate change. In this regard, ponds are influenced by climate change in multiple ways, including increased rate of surface evaporation, reduced hydroperiods, alteration of chemical and biological processes, and increased temperatures (Lamouille-Hébert et al., 2024; Tasker et al., 2022; Ali et al., 2016; Matthews, 2010). As described by Rogora et al. (2018), all the three parts of the Alps considered here are suffering climate change, showing rapid responses at ecosystem level: changes in freshwater organisms were also reported, in terms of increases in solutes, decreases in nitrates and changes in plankton phenology and benthos communities. In the Alps, mean snow depth, snow cover duration and number of snowfall days have decreased since the early 1980s (Laternser and Schneebeli, 2003). Modifications in snow coverage, glacial extensions and frozen periods can affect mountain ecosystem hydrology, biogeochemical processes in soil and water, plant composition and phenology (Rogora et al., 2018). Trends from literature confirm that climate change is occurring in alpine environments, especially during the season of snow accumulation and vegetative growth (Dorji et al., 2020; Acquaotta et al., 2015; Casty et al., 2005).

Land use provide us important insights about the surrounding environment of detected ponds. In particular, the higher number of natural ponds (83%) over than anthropized (17%) found can highlight both the large distribution of pristine environments in mountainous ecosystems and the scarce consideration given to ponds from human activities (Oertli et al., 2010). However, although a pond could not be surrounded by agricultural areas or urban areas (i.e., what we describe as "natural ponds"), this does not mean that it is embedded in a totally natural and pristine ecosystem. In fact, also in high-altitude ecosystems, human direct or indirect disturbances can be present. In the

Apennines, ponds are frequently embedded in an agricultural context (Vitali et al., 2018). In the Alps, the presence of grazing cows moving through areas that are assessed as “natural” in the Corine Land Cover can be very impactful on the high-altitude ponds (Van den Broeck et al., 2019), changing the morphology of the shores and polluting the water with their droppings. For this reason, to assess the real conservation status of ponds it is necessary to perform in situ analysis. In this context, our research could represent an important starting point for conservation activities.

The large distribution of temporary ponds could be in accordance with the low affected nature of high-altitude ecosystems (Ballón et al., 2016); however, while the total number of ponds on the Alps are “natural”, NAP and CAP are characterized by a large distribution of “anthropized” ponds. In the Apennines, anthropogenic pressure has historically taken the form of intensive grazing on high-elevation pastures and short-rotation coppicing in forests (Quaranta et al., 2020; Vitali et al., 2018; Caballero et al., 2009). The relatively recent decline of such traditional practices has progressively changed the mosaic structure of mountain landscapes, with the increase of high-elevation forest coverage (>1.500 m a.s.l.) (Vitali et al., 2018). NAP are historically characterized by burning and accelerated soil erosion, indicating widespread human activity (Branch and Marini, 2014); CAP show significant evidence of human impact on the forests and the development of grazing up to 2000 m a.s.l. since many centuries (Brown et al., 2013); SAP were characterized by the altitudinal expansion of the tree line, experiencing more intensive land uses in the past (Vitali et al., 2018). The widespread historical human impacts on the Apennines influenced distribution and morphological features of ponds. However, while “natural” ponds show with a certain probability to be not-related to human activities looking at satellite images, the nature of “anthropized” ones should be evaluated with on-field samplings.

The evaluation of the pond’s areas highlighted the differences between the zones considered. WA, CA and CAP appear to share the highest values of area. On the contrary, EA, NAP and SAP show the lowest areas. WA and CA are characterized by higher altitudes and lower human activities. The Alps are instead characterized by a larger presence of snow coverage (Paul et al., 2007). The temperatures typical of the spring and summer seasons lead to the snow melting and the formation of ponds (Beniston, 2012). The hydroperiod of these ponds depends on many environmental and geographical factors. Generally, as demonstrated by our results, ponds generated by the snow melting are larger in size than the natural pools which generate at lower altitudes. Furthermore, at high altitudes, climatic variations interact with glacial processes and influence the dynamics of alpine ecosystems (Zemp et al., 2006). This is important also for social implications, considering that mountain glaciers are the major fresh water source for people living in or nearby the adjacent lowlands of mountain ranges (Giaccone et al., 2015). On the contrary, NAP and SAP ponds show statistically smaller dimensions. The difference may lie in the low altitude reached by the mountains present in these regions and the consequent almost total absence of snow coverage. Low altitude ponds are mostly generated and related to phenomena such as precipitation or the infiltration of groundwater (Hayashi and van der Kamp, 2021; Zacharias and Zamparas, 2010). On the contrary, CAP host the highest mountains in the Apennines, and the generation of ponds could be favored respect other Apennines districts from snow melting. Moreover, the highest area values could be explained also considering the influence of those which are supposed to be artificial ponds, showing average area values higher than natural ones. Finally, in EA, present-day glaciers cover an area of about 6.95 km^2 in this mountain group (Seppi et al., 2015; Cagnati et al., 2002). They are generally small cirque glaciers, persisting at low altitude thanks to high accumulation rates of avalanche snow. Also in this case, the low area of glaciers could explain the lower ponds area evaluated.

Comparing altitude, the difference between the six zones could be addressed to the different altitude reached by mountain chains. The Alps host the highest peaks in Italy like Monte Bianco (4806 m a.s.l.), Monte Rosa (4634 m a.s.l.), Monte Cervino (4478 m a.s.l.). The Apennines host, as highest mountains, the Gran Sasso d’Italia (2914 m a.s.l.), Maiella (2795 m a.s.l.) and Monte Velino (2487 m a.s.l.). Moreover, NAP are considered to reach a maximum altitude of 2165 m a.s.l., while SAP host, as highest mountain, the Pollino (2248 m a.s.l.). Altitudinal differences were expected and then confirmed by analysis. However, comparing altitude and area, only low correlation emerged. WA, CA, and EA showed low positive correlations, while NAP, CAP and SAP showed low negative correlations. These results can be explained considering land use and the altitudinal differences previously described: the Alps are characterized by an increase in area as a function of altitude. This correlation is probably influenced by the snow melting, especially at high altitudes, which has caused an increase in pond areas. Another reason can be identified in the vegetal coverage, which was proved to influence the area of the ponds. Water level and vegetation cover show a direct relationship, influencing each other. Water-level change in ponds is considered a disturbance to many aquatic plants (Hayashi and van der Kamp, 2021). Plant cover can instead greatly influence the availability of water in a pond due to continuous water capture (Oertli et al., 2023). Below the ‘nival zone’ where conditions are too cold to support vascular plant life (Verrall and Pickering, 2020), ponds area and water volume are not affected by vegetation catchment. Below the climatic treeline, where vegetation cover increases as altitude decreases (Wang et al., 2023; Qanbari and Jamali, 2015; Wilson and Nilsson, 2009), plant biomass can significatively reduce water availability in ponds, especially during the growing season, which duration in high-altitude environment averages around 160 days (Verrall and Pickering, 2020). On the contrary, in the Apennines, ponds with the largest area were found at lower altitudes. This result is in line with land use, where ponds characterized by anthropic impacts (therefore also artificial) mainly appear at lower altitudes, showing larger dimensions than the natural ones at higher altitudes (but, in any case, not formed due to the snow melting). These results are also in accordance with the Chi-squared tests, where altitude results medium-high correlated with ponds hydroperiod and land use. As described before, especially in the Apennines, an increase in the anthropic impacts on the natural component of ecosystems appeared, especially at lower altitudes. Temporary ponds with larger areas are present at lower altitudes, especially in the CAP. The lower temperatures, typical of high altitudes, could favor a longer duration of ponds hydroperiod. On the contrary, at lower altitudes and lower latitudes, natural ponds are dominant. (Jacobsen and Dangles, 2017). Finally, a correlation emerged between “hydroperiod” and “land use”: the highest number of permanent ponds result also as “anthropized” ponds. Furthermore, permanent ponds are distributed mainly at lower altitudes, supporting the thesis that many of the ponds found and described as "anthropized" could be of artificial origin.

Our findings suggest that ponds are both widely distributed in the Italian high-altitude ecosystems and that their conservation status is highly threatened. Climate change and anthropic pressures can endanger the existence of small waterbodies, especially temporary ones (Xia et al., 2015; Rosset et al., 2010). Although all high-altitude ponds in the Alps are inserted in a natural context, the extreme temperatures of winter and summer can represent a significant risk factor, even for permanent ones (Ali et al., 2016). Considering the prolonged period in which ponds remain frozen and the high temperatures typical of the summer period, their hydroperiod becomes increasingly reduced. Given their value as a source of water for the flora and fauna of these extreme environments (Biggs et al., 2017), it is important to protect them throughout the year. Moreover, ponds support a larger proportion of rare, endemic and threatened freshwater species, and are key elements of blue landscape connectivity (Hill et al., 2018; Céréghino et al., 2010). In addition, ponds deliver multiple ecosystem services and Nature's Contributions to People, including carbon storage and climate regulation, water provision, flood control, groundwater recharge, pollution amelioration, recreation and tourism (Fu et al., 2018; Biggs et al., 2017). Their mapping therefore represents an important first step, especially for policy makers. Identification and geographical localization of ponds represent the basis for the design and implementation of long-term monitoring protocols by policy makers (Oertli et al., 2005). On this context, although it is not easy to intervene to maintain the water regime of high-altitude ponds, water can be made available through the installation of fountains for animals.

However, our results also demonstrate that many high-altitude ponds, especially in the Apennines, are far from being identified, certainly impossible by satellite due to the extensive tree coverage. It is therefore necessary to draw up on field surveys and monitoring plans through in situ censuses and subsequent conservation plans.

Conclusions

We evaluated the distribution of small waterbodies (ponds) in the main mountain ranges of the Italian Peninsula, the Alps and the Apennines, focusing on a crucial yet often overlooked aspect in the literature: the identification and characterization of permanent and temporary high-altitude ponds. Our results highlighted an unrepresented distribution of ponds, where the Alps host the highest number, and the highest total area compared to the Apennines. Moreover, ponds of the Alps can be considered mainly natural, while Apennines’ ponds show an important influence of human activities. Apennines ponds, showing lesser altitudinal distribution and lower area at higher altitudes, appear to be mostly artificial, or supported in their hydroperiod length from anthropogenic influences. Furthermore, a low positive correlation emerged between area and altitude for the Alps and a low negative correlation emerged between area and altitude for the Apennines. The different interactions found depending on the environmental and geographical variables, highlighted the importance to analyze ponds under multiple biological aspects. Moreover, this study raises the question of the importance given to these threatened ecosystems, as they may be more studied and protected. The main limit of this research is the tree coverage, which makes the pond identification from satellite images difficult and incomplete. To the best of our knowledge, this is the first study investigating the distribution of high-altitude ponds in the two principal mountain ranges of Italy. However, lacking an assessment error, mainly due to the large tree coverage, this research is to be considered incomplete. Field surveys are fundamental to determine the correct and complete distribution of ponds, especially for those not detectable by satellite images. Moreover, orthophotos can be an important tool to compare aerial photographed ponds and those found through satellite imagery. The comparison between these data could provide important information about lacking ponds. Future studies are therefore necessary to correctly define errors and to make a complete checklist. The results found could have ecological implications and, in conjunction with assessments of pond presence with on-field surveys, can provide valuable suggestions on the effects of natural and anthropogenic threats on high-altitude ponds conservation and management activities.

Data availability

No datasets were generated or analysed during the current study.

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Compliance with ethical standards

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