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Eco-Hydrogeology and Engineering for the Conservation of Mediterranean Peatlands in Karst: An Interdisciplinary Case Study

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Abstract

Peatlands in mid-latitudes are critical and rare ecosystems, acting as important carbon sinks and hydrological regulators. This study presents an interdisciplinary investigation (geological, hydrogeological and palaeoecological) of the Calatañazor peat bog (Soria, Spain). Through geological mapping, geophysical prospecting, soundings and C14 dating, the evolution of the karst lagoon system is reconstructed. The results reveal a genesis linked to the closure of the valley by a barrier of calcareous tuffs during the Upper Pleistocene, and the sedimentation of lacustrine organic clays during the last glaciation, followed by a phase of active peat formation in the early Holocene (7590–5800 BP). Hydrochemical analysis and piezometric monitoring demonstrate that the peat bog functions as a regional discharge point for the Utrillas Facies aquifer, maintaining critical water table levels (0–1 m) and exerting a self-purifying effect (denitrification). Following decades of degradation caused by agricultural drainage, the research provides a scientific basis for its restoration through an analysis of its structure and hydrological functioning. It concludes that restoring the original water body is technically and hydrologically feasible, as the system exhibits an outflow character downstream, ensuring the conservation of the ecosystem without compromising local water resources. The engineering intervention, carried out between 2025 and 2026, consisted of creating a shallow lagoon and plugging strategic drains. The project demonstrates that the integration of palaeoecology and active management is key to the resilience of Mediterranean wetlands in the face of climate change.

Keywords: wetlands in karst; karst hydrology in national parks; Mediterranean peatlands; barrier tufa peatlands; ecohydrogeology; peatland restoration

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1. Introduction

1.1. Importance of the Hydrological Functions of Peatlands

Peatlands cover 3% to 4% of the Earth's land surface [1]. Most peatlands originated in the Holocene and their deposits record the development of their vegetation. The peatlands that have survived to the present day hold greater biodiversity than other terrestrial habitats. These ecosystems support distinct and unique evolutionary dynamics, driven by a delicate, complex balance of physical and biological elements and processes. Furthermore, they provide ecosystem services, water storage, regulation and purification [2].

Peatlands reduce flood peaks, supply water to hydrological systems when it is scarce and during dry periods, and purify surface or groundwater as it flows through the organic matrix, improving outflow quality. They also protect against water erosion. The effectiveness of these regulatory functions depends on various factors, such as the size and type of peatland, the proportion of the catchment area covered by peatlands, climatic characteristics and the environmental condition of the wetlands [3].

Peatlands provide important ecosystem services, such as carbon sequestration and climate regulation [4], and the provision of habitat for rare and priority species [5].

1.2. Vulnerability of Peatlands to Alterations in Their Hydrological Regime

Peatlands also have great heritage value, as they support a moderate variety of plant life. Some peatlands suffer from local eutrophication, caused by farming and grazing. This degradation significantly reduces the resilience of these environments, which is particularly worrying in the context of global warming and the likely increase in nitrogen-rich rainfall; consequently, restoring the functionality of these natural environments is becoming increasingly urgent.

In general, human activities such as drainage, peat extraction and straightening watercourses have caused hydrological disturbances that, in turn, have impaired the overall functioning of these water-saturated ecosystems. Peatlands also help regulate atmospheric concentrations of carbon dioxide and methane [6]. Restoring wetlands helps to reduce the carbon footprint, and in the 2000s, managers increasingly prioritized hydrology and became more interested in how these ecosystems function. Work then began on ensuring the proper hydrological functioning of these peatlands, with local managers seeking to implement a comprehensive program to restore a large number of them.

1.3. Peatlands in Europe: Assessment and Restoration

Peatlands vary widely, depending on their formation, age, the vegetation they originate from, and their state of decomposition [7]. Peatland landscapes are typical of northern regions; in northwestern Europe, two main types of ombrotrophic peatlands exist: raised bogs and blanket bogs. The latter are found in the coastal areas of western Ireland and Norway. However, peatlands are rare in mid-latitudes, occurring sporadically in the high mountains of Spain, also inland, associated with lake and river systems. Among these, we highlight the peatlands linked to the silting up of lakes formed by tuff dams, as studied in this paper. There have always been ill-fated attempts to exploit them during periods of fuel scarcity, to obtain organic mulch for farmland, or simply to drain them to gain land for cultivation. This was particularly the case in times past when land was far more important than it is today.

Peatlands on the Iberian Peninsula have been described as scarce or having low rates of peat accumulation, largely due to the dry and warm climatic conditions prevailing across most of the peninsula [8,9]. Furthermore, peatlands in this region have also come under severe pressure in recent decades due to a range of human activities, such as drainage for the conversion of land to cropland and to reduce the risk of malaria, overgrazing, afforestation, peat extraction for horticulture, and the construction of wind farms [4,10,11]. In the most severe cases, these ecosystems have disappeared entirely [9]. However, despite these pressures, several areas of Iberian peatlands have persisted, mainly in the high-rainfall mountainous regions of the north, but also in low-energy wetlands (e.g., river plains, estuaries and coastal freshwater lagoons) [8,12].

Peatlands are subject to various forms of protection (e.g., Protected Areas and Designated Areas) [5] and are considered habitats of Community interest under the Habitats

Directive 92/43/EEC [13]; they are also fundamental to achieving the carbon emission reduction targets of the Paris Agreement [14].

1.4. Ecohydrogeology Applied to Peatland Restoration

Peatlands are one of the biosphere's largest carbon reservoirs, and are currently experiencing a drop in the water table due to groundwater extraction, as well as carbon loss driven by climate change. To carry out the conservation and/or restoration of peatlands, palaeolimnology sometimes requires the combination of hydrogeological and ecological parameters to reconstruct their hydrology (e.g., [15]). As shown, our study focuses on a peatland ecosystem dependent on groundwater, subsurface and surface water, and one that requires interdisciplinary convergence for better study and management, which is currently termed ecohydrogeology [16]. Hydroecology integrates ecological and environmental biology sciences with hydrogeology to study organisms, habitats, ecosystems, and management policies that depend on groundwater. In many environments, groundwater discharge and surface runoff intermingle. Research on groundwater–surface water interactions examines the interface between aquifers and rivers, and emphasizes the relationships among the spatial and temporal variation in hydrological, physical, biogeochemical, and ecological factors [17]. Ecohydrogeology is grounded in geology, which largely controls aquifer hydrology and, in combination with streams and rivers, supports the development of aquatic and riparian ecosystems.

To conserve peatlands and restore degraded ones, understanding the local causes of change is essential to develop appropriate responses at the local level [18]. Palaeoecological data provide evidence of past vegetation, its development, past changes, when these changes occurred, and any links to climate change. This helps explain the causes of vegetation degradation in areas where previous palaeoecological knowledge was lacking. Ultimately, this information will contribute to understanding the former habitat, whether and how it can be restored, and the potential consequences of restoration practices. Few studies have used palaeoecological techniques to advise conservationists explicitly, but in recent decades, collaborative studies have been carried out in England and Wales between conservation agencies and palaeoecologists, generating palaeoecological data from peatlands that could serve as a basis for conservation practices (e.g., the Mossdale Moor peatland, [19]) and others [20–24].

The depth of the water table (the distance from the surface of the peat to the water table) is a key factor determining the ecology and functions of peatlands [25,26]. Recent research has suggested that there may be a critical level [27] above which the peatland ecosystem loses most of its services and a shift in the ecosystem occurs. However, no general quantitative assessment of this threshold for healthy ecological peatland functioning is currently available, although Liu et al. [28] showed that when the water table depth exceeded 30 cm in the Dajiuhu peatland (China), the peatland showed a low carbon sink potential. Research on peatlands in northern latitudes shows that a prolonged drought with the water table below 30 cm led to a functional transition from carbon sink to source [29].

Taking a neighboring country such as France as an example, most peatlands are of great natural importance, but a considerable number have been destroyed or damaged by various human activities. Currently, peatlands are included within the scope of the national strategic plan for wetlands, as well as the European Union's international Natura 2000 and LIFE programs. Despite these wide-ranging conservation initiatives, there remains concern about the effects of water extraction, fertilizer runoff and overgrazing on peatlands [30].

For any ecological engineering project, restoration work must be preceded by studies that thoroughly understand the peatland's hydrological and ecological functioning. This will enable effective water management, restoring the original water flows and improving

water retention to reactivate peat formation. The assessment must be tailored to each site and may include the study of surface and groundwater flows (piezometry, hydrometry, physico-chemistry, topography of the surface and the underlying geological substrate), the study of vegetation, geomorphology, etc.

Scientific studies of peatlands can serve a practical purpose: the immediate need for management. For this reason, the main aim of this article has been to enhance our understanding in order to inform environmental managers about the origin and geological and hydrogeological characteristics of a peatland in the Mediterranean region, in an area where there was a lack of prior knowledge. All this is aimed at understanding the former habitat and thus establishing criteria for its eventual restoration, as well as providing support for the feasibility study of the project for the partial recovery of the former peatland, making it compatible with measures to protect the associated peatland in order to ensure its conservation.

1.5. Peatlands in Karst-Origin Lakes in the Mediterranean Region and in Spain

Tufa-barrier lakes and lagoons in Spain are wetlands formed through the accumulation of calcium carbonate, which creates small natural barriers capable of retaining water. Over time, many of these lagoons have undergone a progressive silting-up process as a result of the accumulation of sediments and plant remains. This process has gradually reduced the depth of the water bodies and favored the expansion of vegetation.

In some cases, the accumulation of organic matter under high moisture and limited oxygen has led to the formation of peatlands. These peat deposits are natural archives of considerable scientific interest, as they preserve plant remains and sediments accumulated over thousands of years. Studying them allows reconstruction of past changes in vegetation, climate and environmental conditions. Former tufa-barrier lagoons are therefore important not only from geological and ecological perspectives, but also as palaeoclimatic and palaeoenvironmental records. Peatlands developed within former karstic tufa-dammed lagoons are relatively common in Spain. Their conservation is therefore particularly important, since peatlands are highly sensitive ecosystems that can be severely affected by alterations to the hydrological regime and by desiccation.

1.6. Objectives

Therefore, to address the broader issue of declining Mediterranean peatlands, eco-hydrogeological studies and palaeoecological approaches are essential for their restoration. We hypothesize that the dynamics of many inland Mediterranean peatlands, such as the Calatañazor peatland, were and are intrinsically linked to the evolution of the downstream tuff barrier, and that restoring them requires raising the water table above the critical threshold for organic-matter oxidation. This entails a series of objectives, such as determining the origin and characteristics of the lagoon that preceded the Calatañazor peat bog through its palaeogeographical reconstruction based on the study of Quaternary geological formations, particularly by identifying the nature, thickness, extent and age of the peat bog. This will provide an example of how karst dynamics and hydrology influence the resilience of peatlands in Mediterranean climates. It will also be important to understand the dynamic processes of the system, including the identification and characteristics of the current Quaternary lagoon aquifer/aquitard, a conceptual model of hydrogeological functioning, the seasonal evolution of groundwater levels, and the hydrogeochemistry of the groundwater. Another objective will be the conceptual establishment of the water balance of the current wetland and the calculation of evaporation as a new component should part of the lagoon be restored. Finally, building on the previous findings, we designed and assessed the works and hydrological remediation measures aimed at conserving, restoring and recovering the

site, and we recently completed the works. Hydrological monitoring and control measures have also been designed for the period following the recovery of the lagoon.

2. Site Description

2.1. Historical Background and Legal Framework of the Study Area

Regarding the area under study (Figure 1), the earliest record we have of the Calatañazor peat bog is a brief mid-19th-century account of a pond [31] where high-quality leeches were bred; this reputation has been maintained to the present day through oral tradition. The geologist Pedro Palacios [32] briefly describes the existence of this pond in the chapter on ponds in Soria within his book on the Geology-of-Soria: "In the pastureland of Calatañazor, within a small valley whose bed reveals marl and argillaceous rocks from the Cretaceous period, there is another lagoon, covering an area of some 3 hectares, whose waters are fed not only by rainfall but also by several small springs in the immediate vicinity".

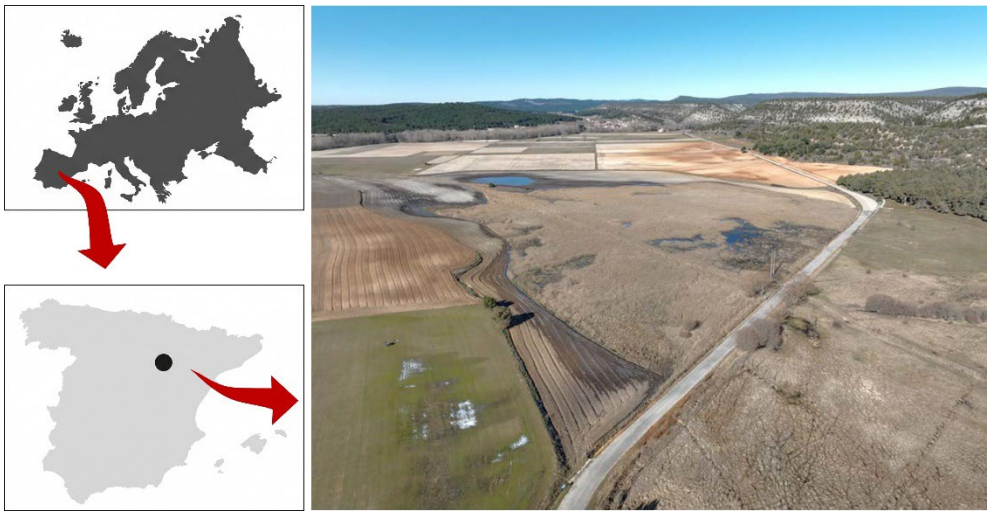


Figure 1. Study area of the Calatañazor peat bog (Iberian Mountain Range, Soria, Spain). A drone view looking north, showing the bog's reed bed and waterlogged areas, as well as the terrace of white, tuffaceous farmland that blocks the valley of the Majallana stream, a tributary of the River Avión. In the background on the right is the limestone mountain range of Cabrejas. At the bend in the road that crosses it lies the juniper grove with its distinctive trees.

It is important to note that this area had long held the legal status of a Public Utility Forest under the name Dehesa Carrillo, registered under number 248. This means that it was intended for livestock and forestry use, combining the benefits of grassland and juniper woodland for the feeding and climatic protection of livestock, which at that time was a very important resource, and in villages common land was always set aside for this purpose. Following the Madoz confiscation in 1855, and as a countermeasure, the Catalogue of Public Utility Forests was created in 1862 as a pioneering conservation measure; this forest was included in the catalog, which ensured its survival to the present day.

However, during the economic hardship of the 1940s, the irrigation channels were deepened to lower the water table and drain the lake, thereby reclaiming new land for cultivation; land was then much more valuable than it is now, and survival depended on it. The 1956 aerial photograph of the study area shows the Dehesa de Calatañazor and the reed bed area crossed by the road and partially cultivated (Figure 2). However, human impact on the lagoon began much earlier. Since ancient times, agriculture and the use of the Dehesa for livestock have created a landscape of meadows and farmland that extends

continuously across the upper half of the area. In this study, we have also been able to verify that the lake phenomenon, both in space and time, was considerably larger than we initially believed, since the original and primitive lagoon not only included the current reed bed and surrounding low-lying fields, but also the entire Dehesa pastureland up to its upstream section, over a length exceeding one kilometer. We assume that the old path crossing the Dehesa in Figure 1, east of the road, marked the boundary of the old lagoon in recent times.

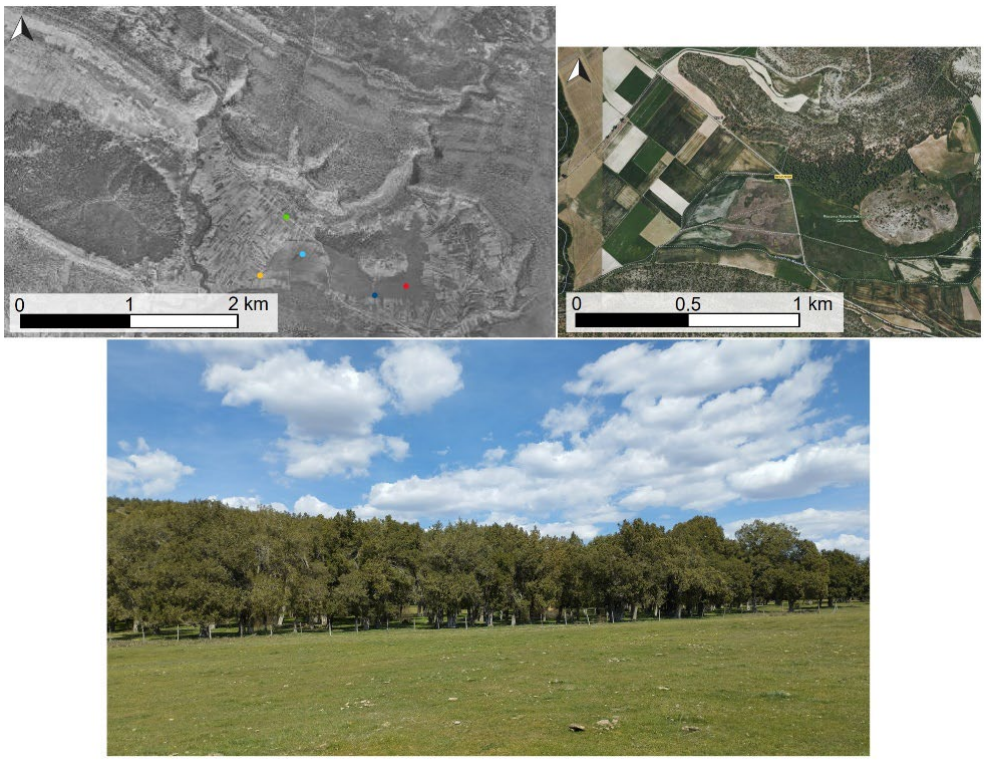


Figure 2. (**Top left**) An orthophoto from 1956 of the study area, showing the Dehesa de Calatañazor (red dot) and the reed bed area (light blue dot), crossed by the road (green dot) and partially cultivated. The dark blue dot marks the old track and the yellow dot indicates the start of the drainage channel. (**Top right**) Current orthophoto: to the right of the road crossing the reed bed lies the peat bog, which has been used as pastureland for livestock since medieval times. (**Bottom**) Detail of the juniper grove in the Calatañazor pasture.

Subsequently, the current road was built, along with the drainage systems and changes in land use for agriculture, which were authorized due to the urgent need for food in the post-war period and which still remain today, as can be seen in the historical series of aerial photographs. In the 1956 aerial photograph, the extent of the grassland area can be seen, which coincides with the boundary of the public woodland, and the drainage systems to the west of the road are already visible.

Furthermore, this lake basin also contained peat deposits, and a 1975 pollen study [33] confirmed that Pinus species is dominant in the flora of the Calatañazor peat bog. Although no C14 dating was carried out on these organic deposits, they were dated to the early Holocene. A mining application was subsequently submitted in 1992. The operation aimed to extract peat for commercial use in gardening for the Expo and the Barcelona Olympics. Its status as a Public Utility Forest prevented the project from proceeding, as the forestry authorities issued a negative.

For these reasons, as early as 1998—almost 30 years ago—Article 13.4 of the Reserve's Natural Resources Management Plan already stated that efforts would be made to regenerate the former wetland area west of the road from Calatañazor to Muriel-de-la-Fuente. Similarly,

the provisions recognize and highlight the need to maintain water and peatlands quality and prevent their alteration.

2.2. The Sabinar-de-Calatañazor Nature Reserve and the Fuentona de Muriel Natural Monument

The first measure to protect the peat bog was the classification, in the 19th century, of the land owned by Calatañazor Town Council and the local authority of Aldehuela-de-Calatañazor as public woodland, as previously mentioned. It is currently part of a nature reserve known as 'El-Sabinar-de-Calatañazor', a protected area located in the province of Soria in the autonomous community of Castilla-y-León (Spain). The area's main feature is a forest of Spanish junipers (*Juniperus sabina*) situated next to the peat bog, which is home to long-lived, large specimens. Some trees exceed 20 meters in height, and there is also an extraordinary specimen with five branches that is included in the catalog of notable trees of Castile and León. Most of the trees are over 300 years old and have grown exceptionally well due to the site's fertility and humidity, which are not typical of the conditions in which junipers grow [34].

There are several reasons for this, the main one being that this area has been used as a silvopastoral pasture (grazing land for livestock), which has established a nutrient cycle between the grasslands outside the forest—which coincide with the peat bog at its thinnest point—and the forest, which has served as a refuge for the livestock and has also provided food during the most unfavorable seasons. Livestock has prevented the encroachment of scrub and other forest species and greatly improved soil fertility; the land is also situated on a hillside at the bottom of a valley with deep soils and a relatively shallow permanent water table. The scenario one might imagine, had it not been designated as public woodland, would be entirely agricultural land and some treeless pasture.

On 11 June 2000, the Act designating the Sabinar-de-Calatañazor Nature Reserve was passed. Before this declaration, the Natural Resources Management Plan had been prepared under Law 8/1991 on Natural Areas in Castilla-y-León, approved by Decree 143/1998 of 16 July. The protected natural area coincides with the 74 hectares of the Dehesa-de-Carrillo public woodland.

The Sabinar-de-Calatañazor is not a typical juniper forest. Instead, this site stands out for its unique character, featuring exceptional specimens of *Juniperus thurifera*. It also has a tree density per hectare that far exceeds the norm for this type of woodland. These qualities make this forest worthy of legal protection.

The Dehesa-de-Carrillo has traditionally served as communal pasture. Its current uses include recreation, dry farming and grazing. Grazing in the cultivated area takes place on stubble fields, whilst the rights to graze the remainder of the land are auctioned off for horses or cattle.

The monumental nature of the junipers in the Dehesa de Carrillo has been noted by various authors, such as Luis Ceballos [35], who makes specific mention of the "unusual density and size of our trees". Costa et al. [36] also refer to the Calatañazor grove as one of the densest and finest white juniper groves in the world.

The Calatañazor juniper grove is therefore an exceptional site, situated on high-quality, deep, moist soil enriched by centuries of organic matter, which has allowed the junipers to flourish to an unusual degree. The continued use of the land for grazing prevents encroachment by shrubs and other tree species, such as holm oaks and gall oaks.

These values have been key to its designation, first as a Nature Reserve and subsequently as part of the Special Area of Conservation (SAC) 'Sabinares-Sierra-de-Cabrejas', code ES4170029, under Royal Decree 1997/1995 of 7 December, which establishes measures to help ensure biodiversity through the conservation of natural habitats and wild fauna

and flora. These protection designations mean it is part of the European ecological network known as the Natura 2000 network.

These designations aim to conserve this unique natural area, along with the traditional practices and customs long associated with it, while promoting its natural and ethnological values among the local population. The Sabinar-de-Calatañazor is complemented by the Monumento-Natural-de-la-Fuentona, located nearby. Between these two areas lies the Calatañazor Juniper Grove Park House, located in the Santa Coloma Palace, which serves as an interpretation center for both sites. It houses the interpretation and administrative facilities for both natural areas. As mentioned, alongside the Calatañazor Sabinar and lagoon lies the Fuentona Natural Monument, whose main feature is a karst spring that rises in a naturally beautiful setting and averages around 1000 L per second. This spring is the natural outlet of the calcareous aquifer of the Sierra de Cabrejas, and its incrusting waters, as we shall see, were responsible for the formation of a tuff terrace that acted as a lateral dam on a tributary stream and led to the creation of a lagoon during the Pleistocene (Figure 1).

Article 13.4 of the Natural Resources Management Plan for the Nature Reserve states that efforts will be made to restore the former wetland area located to the west of the road from Calatañazor to Muriel-de-la-Fuente.

2.3. Climate and Botanical Characteristics of the Area Surrounding Laguna-de-Calatañazor

The climate in this area is Mediterranean, with relatively cold winters and average annual rainfall of around 750 mm in this part of the Sierra de Cabrejas, peaking in spring; rainfall is evenly distributed across this plateau, and winter snowfall is not uncommon. The harsh continental climate of the area, the poor quality of the soil—unsuitable for cultivation on the limestone plateau of the Sierra-de-Cabrejas, and the high rate of water infiltration and low water retention due to the presence of karst make this plateau markedly arid. Yet it has nevertheless preserved the most extensive and best-preserved forests of Spanish juniper (*Juniperus thurifera*) in Europe, one of the trees most resistant to these conditions, capable of withstanding very intense cold, intense summer heat and prolonged droughts. In fact, it is a 'wildcard' species as it occupies spaces where other trees cannot survive. Occasionally, it shares territory with holm oaks (*Quercus ilex* subs.) and other less common tree species [37].

However, the Sabinar-de-Calatañazor does not stand on limestone; rather, it is rooted in the sands of the Utrillas Facies and Cretaceous marls. This is the geology of the substrate in the area surrounding the wetland, which is characterized by alternating cultivated land and forested areas dominated by the Spanish juniper (*Juniperus thurifera*), accompanied by *Quercus ilex* subsp. *ballota* (Desf.) Samp in the sunnier, drier areas, and primarily by *Quercus faginea*. In areas with more developed and cooler soils. In addition to the nearby pastureland dominated by *Juniperus thurifera*, with trees of extraordinary size (atypical for this species in these localities), designated as a Nature Reserve (Figure 2), the surrounding areas also feature *Juniperus communis* and other species of the genus *Pinus* (primarily *Pinus nigra* Arnold) [38].

Most of the former Laguna-de-Calatañazor is now dominated by a reed bed (*Phragmites australis* (Cav.) Steud.) (Figure 1), although to the east of the road there remains a wet meadow dominated by species of the genus *Carex* (including *Carex caryophyllea* cf. Latourr., several species of willow (*Salix* spp.), *Scirpus holoschoenus* (L.) Sojak, *Juncus* spp., and other plants typical of wet and temporarily waterlogged areas (e.g., *Lamium hybridum* Vill., *Dipsacus sativus*, Honk., *Ranunculus* gr. *montanus* Wild., *Senecio* gr. *doria*), Drainage ditches are visible, allowing species typical of wet grasslands (*Cruciata laevipes* Opiz, *Poa tivialis*) to colonize the meadow, with some indicators of nitrification due to its use as pasture by

livestock (e.g., *Plantago media* cf., *Bellis* sp., *Rhinula veris*. or the aforementioned *Dipsacus*). Some shrubby elements are also present (*Rosa spinosissima*, *Prunus spinosa*).

2.4. Hygroturbic Records Containing Palaeoenvironmental Information

The Calatañazor peat bog provides a palaeoenvironmental record based on a survey carried out in the 1970s [33]. At that time, the lagoon had already been drained for agricultural use, and the core recovered reached a depth of 4 meters, with materials ranging from peaty sands at the top to clearly organic peat at the bottom. The water table was located at a depth of 106 cm and was studied using palynological methods, although no dating of the sediment was carried out. The abundance of *Pinus* pollen, as well as the scarcity of *Juniperus*, is striking in the record. The author assumes a chronology corresponding to the early to middle Holocene, although the pollen pattern is not entirely consistent with this chronology, due to the scarcity of *Corylus* in the sequence.

There are not many studies on peatlands in this part of Spain and, apart from a few on the characterization of alluvial peatlands in Guadalajara [39], as regards palaeopollen studies at other relatively nearby Holocene sites with palaeoenvironmental data, we may cite the work of García Antón et al. [40] on the Quintana Redonda peat bog, which reveals significant similarities to those of Calatañazor. Both studies were carried out in the province of Soria, at an altitude of approximately 1000 m, and show a similar landscape. A dominance of tree pollen is observed, particularly of the genus Pinus, which maintains a constant level of around 80%. The Quintana Redonda study covers approximately the first half of the Holocene, which would coincide with Menéndez Amor's hypothesis regarding the chronology of the Calatañazor site. Also, very close by is the Serna peat bog in Hinojosa-de-la-Sierra (Soria), situated in an abandoned meander of the River Duero, where Pinus sylvestris from the Upper Pleistocene was found [41].

To find other sites in the Duero basin, one must look to other regions, such as the Cerrato area in Palencia (Espinosa de Cerrato [42]), where an excellent site was recorded comprising 14 meters of pollen-rich layers spanning the entire Holocene. The dominance of Pinus is also notable until anthropogenic times, at which point it declines. The proportions of Quercus, in all cases, are low and variable, but remain constant throughout the sequence.

In the province of Burgos (Spain), a single borehole was drilled covering the Late Glacial period [43]. This study shows that *Pinus* and *Betula* dominated until the Middle Holocene, with a decline in tree cover, likely linked to early human activities.

Finally, at the Carrizal lagoon in Segovia (Spain), at an altitude of 860 m [44], the start of the Holocene is also recorded. Although the proportions of tree pollen are slightly lower than those recorded at other sites, they are more irregular throughout the record. The Quercus pattern also remains consistent.

3. Materials and Methods

To achieve this study's objectives, we adopted a multidisciplinary methodological framework that integrated historical and documentary analysis, environmental characterization, geological mapping, geophysical surveying, direct subsurface investigations, radiocarbon dating, hydrogeological and hydrochemical monitoring, meteorological analysis, analysis of historical aerial photographs, monitoring of restoration work, and the legal management framework. Figure 3 summarizes the overall methodological workflow.

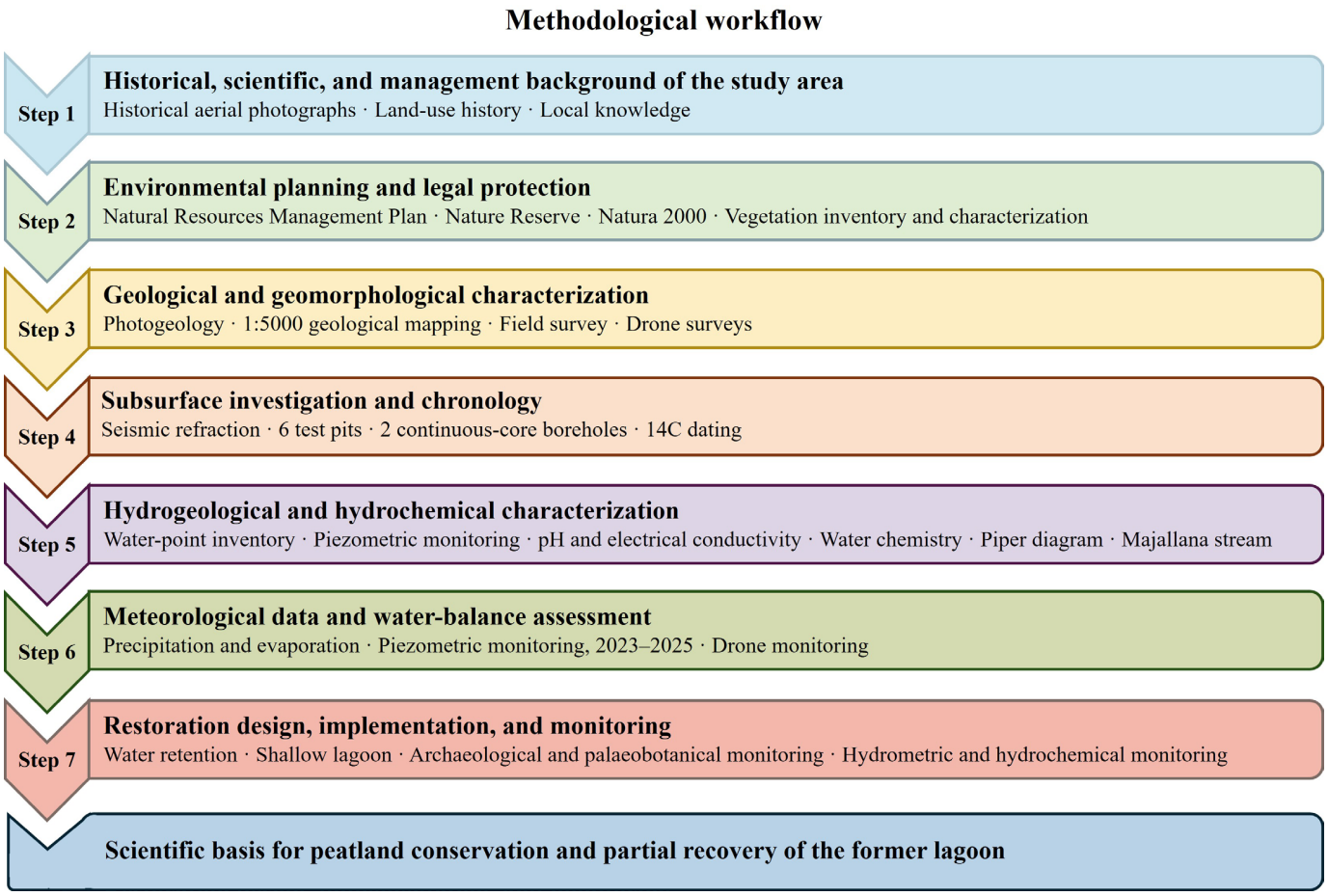


Figure 3. Flowchart of the multidisciplinary methodology used to characterize the geological evolution, hydrogeological functioning, and restoration of the Calatañazor peatland and former lagoon.

3.1. Study-Area Background, Management History, and Protection Framework

Before the Sabinar de Calatañazor was provisionally designated as a Nature Reserve in 1992 and the nearby Fuentona de Muriel was designated as a Natural Monument in 1998, the forestry administration responsible for this Public Utility Forest—including one of the authors of this study (J.M.M.C.)—prevented the commercial exploitation of the peat deposit for horticultural purposes. In parallel, together with another author (E.S.P.), who represented the University on the Reserve Management Board, the available historical and scientific information on the peatland was compiled.

The land-use history was reconstructed using historical aerial photographs, existing documentary sources, direct knowledge of the site, and information provided by local farmers and livestock owners.

Subsequently, the Natural Resources Management Plan that preceded the definitive designation of the Sabinar de Calatañazor Nature Reserve in 2000 was prepared. This work included a vegetation inventory and botanical characterization of the protected area, paying particular attention to the exceptionally developed Spanish juniper woodland adjacent to the peatland. These natural values were instrumental in the area's subsequent incorporation into the European Natura 2000 network. The peat and wetland sediment record was also evaluated for its paleoenvironmental significance relative to other peatlands in this region of Spain. The management plan explicitly identified peatland conservation and regeneration as management objectives.

3.2. Geological Mapping and Geomorphological Characterization

A 1:5000-scale geological map of the main Quaternary superficial formations and underlying Cretaceous bedrock units was created using a combination of photogeological interpretation, drone surveys, and intensive field mapping.

The primary objectives were to delineate the extent of the tufa terrace that acted as a natural dam, characterize the peatland deposits, and determine the origin of the lagoon that existed before peat formation occurred. The survey also established the geologic basis for identifying the hydrogeologic units that sustain the wetland.

3.3. Seismic Refraction Survey

A seismic refraction survey was conducted to estimate the depth and geometry of the peat deposit and the underlying Quaternary lacustrine sediments. This was particularly relevant in sectors where access by drilling rigs and excavators was severely limited.

Because the acquisition spreads were generally less than 48 m, we used a hammer as the seismic source. Thus, three measurement campaigns were conducted, comprising several profiles up to 50 m long with geophone spacing ranging from 1.5 to 4 m (Figure 4).

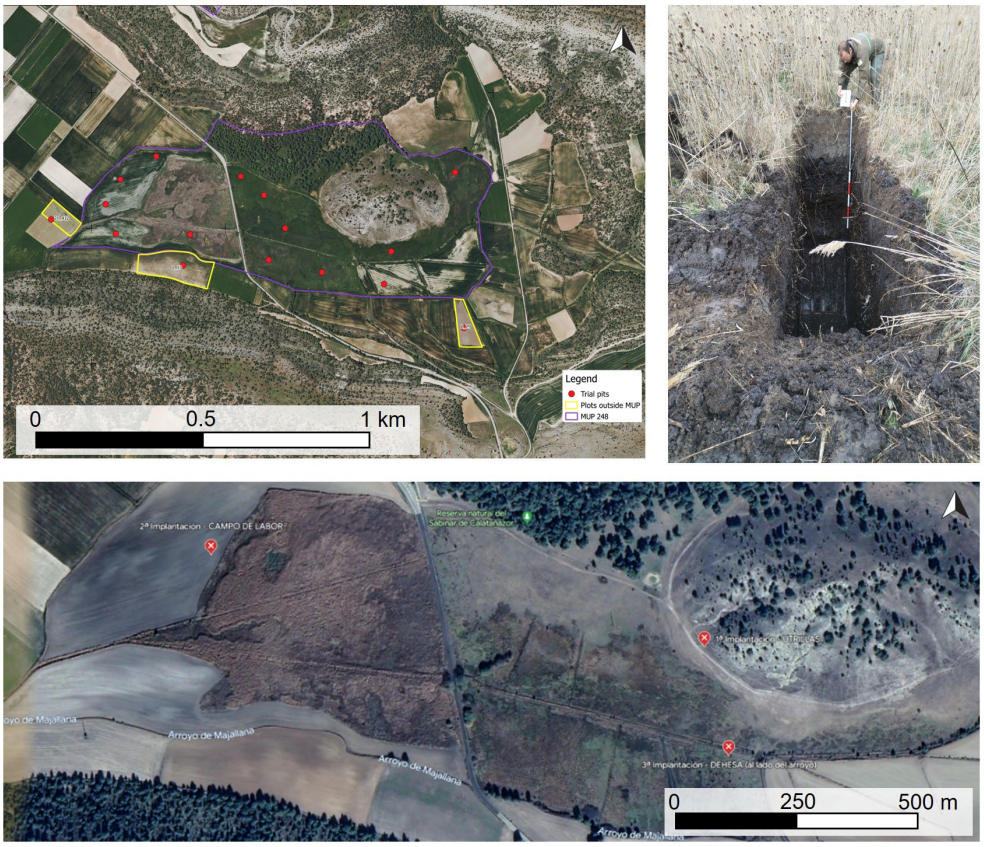


Figure 4. (**Top**) Location of test pits and boreholes. The photograph of the test pit shows a topsoil layer and, beneath that, black or brown peat. (**Bottom**) Location of the seismic refraction survey test sites.

The geological interpretation of the seismic profiles was supported by information from an existing borehole (S1 in Figure 5), which provided an independent estimate of the depth of the peat and underlying lacustrine clay deposits. Additional seismic tests were carried out over exposed Utrillas Facies sands to obtain reference seismic velocities for the geological substrate.

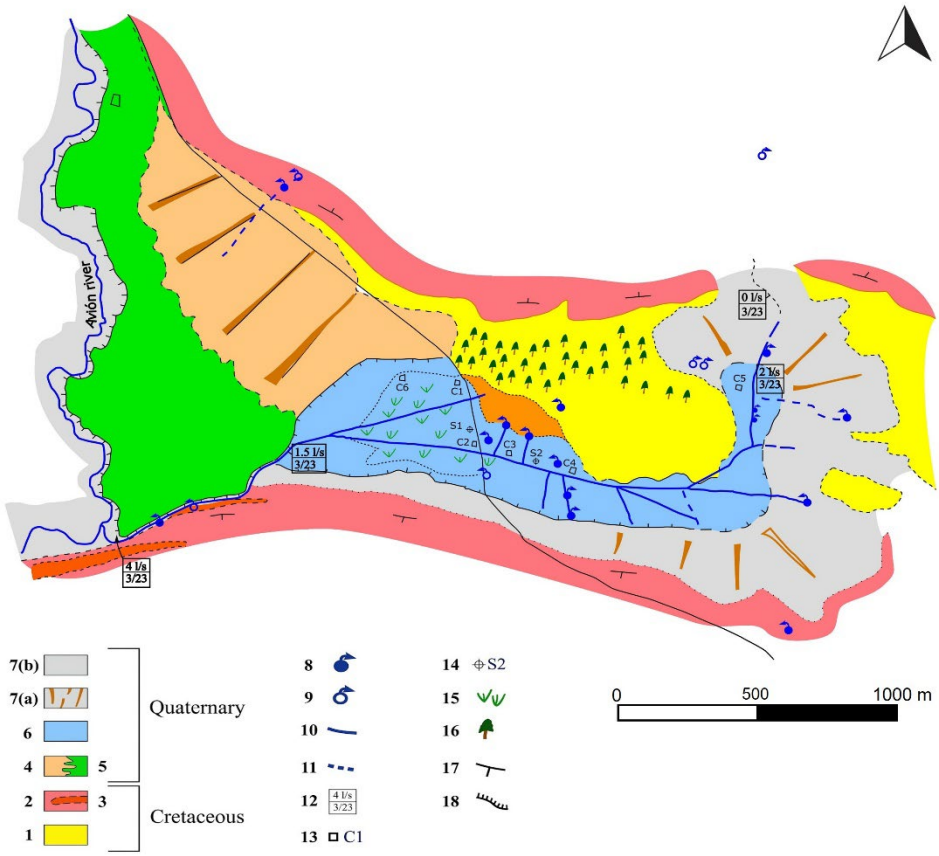


Figure 5. Geological map of the area surrounding the Calatañazor peat bog: Geology. Substrate: 1. Utrillas facies: white sands, clays. 2. Marls and marlstones. 3. Limestones. Quaternary surface formations: 4. Terrace of pulverulent tuff. 5. Glacis. 6. Sediments of lacustrine origin. 7. 7(a) Colluvium-glacis 7(b). Alluvial deposits of the River Avion. Hydrology: 8. Permanent springs. 9. Ephemeral springs. 10. Permanent watercourses or irrigation channels. 11. Ephemeral watercourses or irrigation channels. 12. Gauging points. Others: 13. Test pits. 14. Boreholes. 15. Reed beds. 16. Juniper thickets. 17. Strike and dip of the strata. 18. Erosion escarpments.

Data acquisition was performed using a 12- to 24-channel ABEM Terraloc Mark 03 digital multichannel seismograph. We used 12 to 24 vertical geophones with a natural frequency of 28 Hz. These relatively high-frequency sensors improved identification of the first arrival of P waves, reduced the influence of surface wave energy, and facilitated interpretation of travel time curves.

3.4. Direct Subsurface Investigations and Radiocarbon Dating

Six test pits were excavated to depths of up to 4 m to determine peat stratigraphy, collect sediment samples, and identify the water table position. The scope of these investigations was limited because machinery could become unstable or sink in the saturated ground.

The team also drilled two rotary boreholes, each approximately 5 m deep with continuous core recovery, to characterize the lagoon infill stratigraphy, obtain peat samples, and determine groundwater levels. Electrical conductivity and pH were measured in situ, and groundwater samples were collected for chemical analysis. Both boreholes had piezometric tubes and protected wellheads to enable periodic groundwater-level measurements using an electrical water-level probe. Recovered sediment cores were stored in core boxes and refrigerated before shipment for laboratory analysis.

Peat samples collected from the test pits and boreholes were selected for 14C dating. Three samples were analyzed: two from the base of the peat sequence and one from the

underlying gray lacustrine clay to determine the maximum age of peat accumulation. Radiocarbon analyses were performed by Beta Analytics Laboratory. The team did not sample the calcareous tuffs forming the Avión River terrace for dating because their earthy texture and low likelihood of yielding reliable results made them unsuitable.

3.5. Hydrogeological and Hydrochemical Characterization

A comprehensive inventory of water points was compiled to define, as far as possible, the piezometric configuration and hydrogeological behavior of the groundwater system supporting the former lagoon and the present peatland.

We measured electrical conductivity and pH in situ at selected water points and collected groundwater and surface-water samples for chemical analysis. We determined major-ion concentrations to characterize the hydrochemical facies and construct a Piper diagram.

The hydrogeological assessment also incorporated several years of direct field observations of the Majallana stream, including its behavior during high-flow and low-flow conditions and the episodic activation of the trop-plein karst overflow spring located in its headwaters.

Spring and stream discharges were measured using a **micro-current meter** and the **volumetric bucket method**. Drone surveys were carried out before and after the restoration works in order to monitor changes in the extent of the waterlogged area and open-water surface.

3.6. Meteorological Data and Water-Balance Assessment

We evaluated direct evaporation using records from the Soria-capital meteorological station, located about 29 km from the study area at an elevation of about 1100 m and under broadly comparable climatic conditions. We also compiled monthly precipitation records from the same station. The station is identified as AEMET station 2030 and World Meteorological Organization station 08160.

Because the individual components of the water balance cannot all be quantified with sufficient accuracy, we assessed the system's integrated hydrological response directly. Groundwater levels were systematically monitored for nearly two years, from May 2023 to March 2025, in the two piezometer-equipped boreholes. In parallel, repeated drone surveys were used to monitor changes in the extent of open water and waterlogged areas within the lagoon–peatland system, in collaboration with environmental officers and technical staff from the Soria Environmental Service.

3.7. Restoration Design, Implementation, and Monitoring

We prepared a preliminary technical report based on the geological, geophysical, hydrogeological, and hydrochemical information obtained. This report served as the scientific basis for restoring the Dehesa de Calatañazor lagoon and associated peatland.

The report included an initial characterization of groundwater levels and water quality, a design for hydrological restoration measures, and a monitoring and evaluation program definition. It also documented the administrative and institutional processes necessary to reconcile the interests of the public and private stakeholders involved in implementing the restoration. The restoration work included implementing water retention measures and excavating a shallow lagoon in the center of the reed bed. The team removed approximately 1200 m^3 of reed biomass and 3600 m^3 of organic agricultural topsoil. The excavated soil was placed on adjacent, flood-prone agricultural plots to raise their ground elevation. Archeological and paleobotanical monitoring was carried out during excavation, though no significant findings were recorded.

Finally, a hydrometric and hydrochemical monitoring program was established to evaluate the system's response after restoration and the effectiveness of the implemented measures.

Groundwater levels were measured manually across the monitoring network using a portable electrical water-level meter equipped with a millimeter-graduated cable (KLL series, SebaKMT, Baunach, Germany; ±1 mm accuracy). Measurements were taken from a fixed reference point at the top of the well casing and converted to piezometric head elevations (m a.s.l.). Based on this geological and hydrogeological data, a preliminary report was drawn up [45] which has served as the basis for this article. The report addresses fundamental yet useful issues when considering the restoration of laguna-de-la-Dehesa-de-Calatañazor, such as the initial determination of water table levels and water quality, as well as the design of the hydrological correction works and the planning of measures for monitoring and evaluating the restoration measures.

4. Results

4.1. Geology

4.1.1. The Geology of the Bedrock of the Basin of the Former Laguna-de-la-Dehesa-de-Calatañazor

The basin or depression of the former Laguna-de-Calatañazor is a small, elongated valley running east–west, situated at the heart of an anticline that has been cut through by the Majallana stream, which also runs in the same direction. The valley is surrounded on all sides by medium-height hills, except to the west, where the stream flows naturally into the River Avión, into which it empties.

This anticline closes periclinal towards the east, meaning that the valley is surrounded by slopes where the various strata described briefly here are exposed; these can be traced in the geological diagram in Figure 5.

Right in the central part of the core, the oldest layers corresponding to the Lower Cretaceous Utrillas Facies are exposed, and these likely account for 80% of the substrate beneath the sediments of the lagoonal facies (Figure 5). Thus, from bottom to top, and following the nomenclature of the 1:50,000 geological maps, the following are distinguished [46,47]:

An alternation of 600 m of gray and red clays with poorly consolidated white sandstones. Above this lies an alternating sequence of variegated sandstones and clays 100–300 m thick, also from the Lower Cretaceous continental sequence. This is followed by a 13 m section of marl and 40 m of limestone with marly interbeds, now in the Upper Marine Cretaceous. Above these lie about 30 to 50 m of yellowish marl, followed by about 50 m of gray and beige nodular clayey limestone. Further up lie some 50 m of nodular limestone. Overlying these, in a discordant relationship, are the continental Tertiary sediments, consisting here of conglomerates and red marls over 100 m thick.

4.1.2. Geology of Surface and Lagoon Formations

Based on the detailed geological mapping shown in Figure 5, field observations, and the geophysical surveys, test pits and boreholes carried out, we can distinguish the following geological formations:

- The tuff terrace of the River Avión, which extends across a broad plain on its left bank (Los Tobares). It is a flat, level surface covered with fields of very white crops (Figures 1 and 5). These powdery, earthy tuffs, suitable for cultivation, were deposited by the incising waters of the Avión River, similar to lacustrine chalk. In the Majallana valley area, this terrace widens at its base. The Avión River has cut into this terrace, creating an escarpment between 4 and 8 m high, and between 1.5 and 2.5 m above the

lagoon area, due to the excavation by the Majallana stream. Its maximum thickness is probably around 8 or 9 m. The age of this terrace is unknown, but it is certainly from the Upper Pleistocene.

- Glacis: an extensive, sub-horizontal deposit, with a slight slope toward the valley. It is contemporary with the Avión tuff terrace. On the left bank of the Avión, it forms a tuff terrace or glacis. Here it is a sedimentary glacis, formed at the expense of the erosion of the Utrillas and the Cenomanian marls. However, at the upper source it may be an erosional glacis. It is formed at the expense of the reddish materials of the Utrillas and the Cretaceous marls. This surface geological formation is used for farmland and merges seamlessly with the farms on the tuff terrace to the south. The boundary between the tuff terrace and the glacis is indistinct and gradual. Different colors mark it (white for the tuff, and reddish for the glacis). Across the rest of the basin, this glacis surrounds the Dehesa de Calatañazor, and covers the slopes. It is more of a glacis-colluvium formed by erosion of the immediate Cretaceous marl outcrops, and perhaps some Utrillas facies. This formation has been used for farmland.
- Sediments of lagoon origin. They occupy the valley floor, where the reed bed is located, surrounded by farmland, most of the grazing pasture and some cultivated fields that also flank it. According to the surveys carried out, the sediments appear to comprise several distinct facies (Figure 6).
- Lacustrine clays. Resting on the Utrillas facies substrate are gray clays containing lacustrine organic matter, which have always been detected below the peat level. However, they have not been penetrated in all test pits and boreholes. According to test pit 6 and borehole 2, they could be more than 2 m thick. According to the geophysical survey carried out in the central area of the former lagoon, near the current outfall, the clays are detected to a depth of at least 6.5–8 m, with the bottom likely occupied by Cretaceous marl. According to the refraction seismic survey results, in the Dehesa area near the wooden pontoon crossing the Majallana stream, the clays lie beneath a thin peat layer and reach 4 m depth, resting on the Utrillas Formation. Upstream of Dehesa, the pit appears to disappear or become thinner. This is the only clay type found beneath the topsoil in this area, though this is not entirely certain. C14 dating has assigned an age of 11,450 ± 40 BP to the upper part of the clay layer, placing us firmly in the Upper Pleistocene. The clay layer is at least this old, with the remainder likely covering the post-glacial phase within the Upper Pleistocene. But it may be even older. The age of the closing tuff terrace is probably Upper/Middle Pleistocene.
- Peat layer. According to the refraction seismic data, a peat layer between 5 and 7 m thick is located near the outfall, with the contact with the underlying clay at a depth of approximately 6.6–8 m. According to the test pits, the thickness is less than 2–4 m in the central area, in the reed bed, and it thins out upstream (C-4, refraction seismic survey at the Dehesa pontoon), eventually disappearing at the upper tail (C-5), as mentioned. A tentative boundary has been drawn in Figure 6 to indicate its extent ("peat zone"), to the east of which there would, in principle, be little development. In this section, characteristic brown clayey peats, usually found in the upper part, can be distinguished from other black organic peats. The C14 dating yielded the following values: 5800 ± 30 BP for the upper part of the peat layer, and 7590 ± 30 BP for the lower part. In other words, the peat formation process is confined between these two dates.
- Topsoil. Above this lies a layer of brown, clayey topsoil rich in organic matter, with a depth of between 0.35 and 1.2 m.

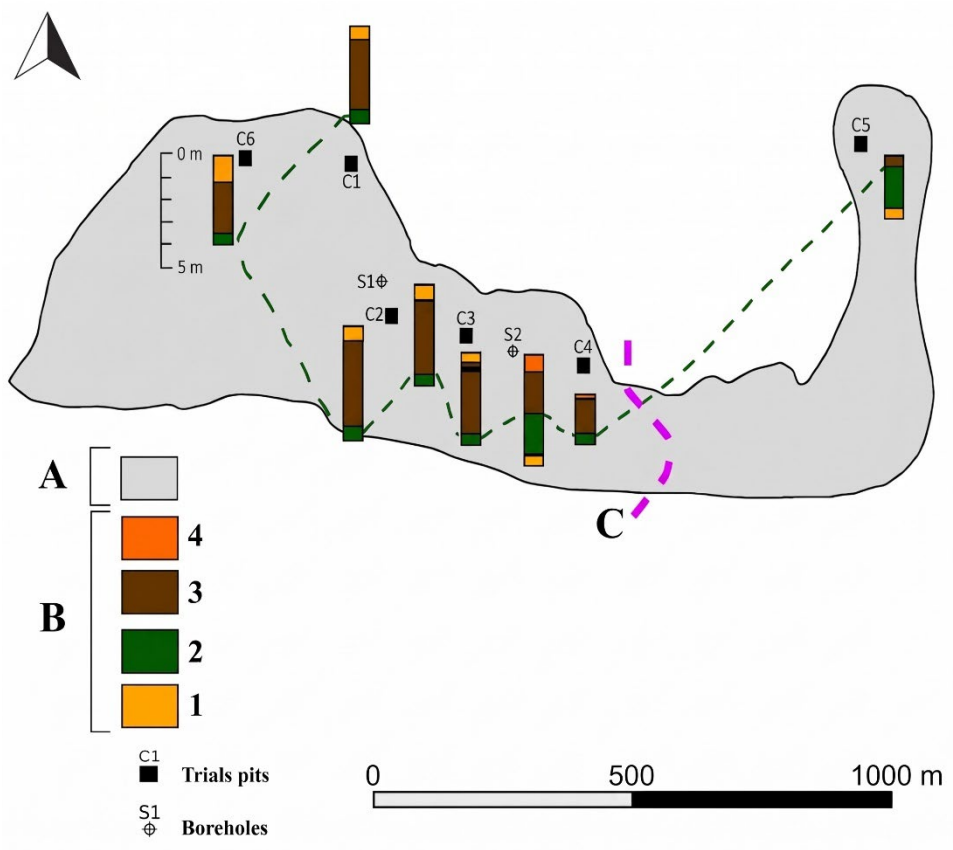


Figure 6. Stratigraphy of the lagoon aquifer deposits based on test pits and boreholes. A. Lagoon area under study. B. Lithologies identified in test pits and boreholes. Substrate: 1. Utrillas facies: sands, pebbles and clays. Lagoon facies: 2. Gray clays with organic matter. 3. Peat (undifferentiated). 4. Cultivated soil, brown clays with organic matter. C. Boundary of the area dominated by peat (western zone).

Finally, we note a small alluvial deposit confined to the bed of the Avión River.

4.2. Hydrogeology of the Former Laguna-de-Calatañazor Pastureland

4.2.1. Definition of Aquifers and Aquitards

Substrate: regarding the hydrogeology of the substrate, the sands of the Utrillas facies have low permeability but retain moisture; in low-lying areas, the water table remains relatively stable over time. This is the case with the Charcas-de-Carbonera (near Soria), former abandoned sand quarries where the ponds remain filled with water all year round. The Cretaceous marls are impermeable, but contain intercalations of limestone which explain the existence of springs such as Las-Fuentezuelas or the outflows into the lower reaches of the Majallana stream before it joins the Avión. The calcareous Cretaceous is highly permeable, and there is a trop-plein or overflow spring that flows sporadically at a rate of over 80 L/s.

In the Quaternary period, peats are highly porous but not very permeable. Earthy tuffs and glacis have moderate permeability. All the clayey lacustrine sediments are saturated with water, and a great deal of water seeped out of them during the test pits, so they cannot be all that impermeable.

4.2.2. The Aquitard of the Lagoon

The lagoon aquifer is formed mainly by Quaternary sediments (Upper Pleistocene and Holocene) and underlying peat and clay, which together form a significant groundwater

reservoir. The aquifer boundaries are very clear and correspond to the area shown in Figure 7. This figure is a hydrogeological diagram showing the aquifer's boundaries, tentative isohyets, and the locations of water points, streams, and drainage or irrigation ditches. It is a flat aquifer with very limited vertical extent, not exceeding 10 m, and a fairly flat substrate morphology. The Quaternary aquifer shows significant but fairly constant vertical heterogeneity and variability: as mentioned, it consists of at least three layers: clay at the bottom, with peat and topsoil above. It also varies laterally, the peat layer appears to decrease and disappear upstream of the Majallana stream, while the clay layer and topsoil remain; this variation logically influences porosity and permeability.

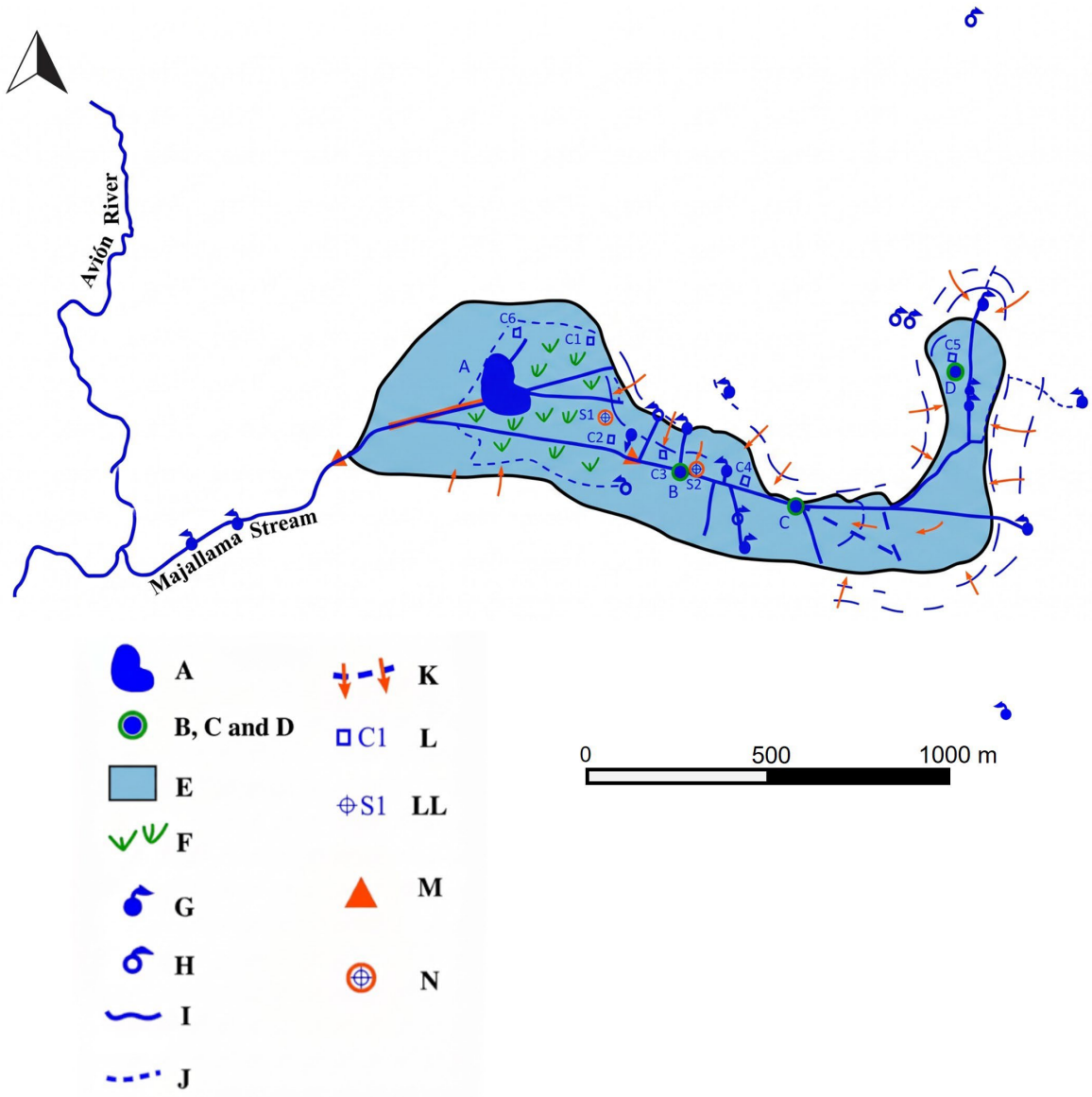


Figure 7. Quaternary lagoon aquifer feeding the Calatañazor peat bog. The location of the proposed lagoon (A) is shown, as well as the planned watering holes and amphibian ponds (B, C and D). Water flow monitoring stations, piezometric measurement points and water quality monitoring points are also indicated. Key: E, lagoon aquifer. F, reed bed. G, permanent springs. H, ephemeral springs. I, permanent watercourses or irrigation channels. J, temporary watercourses or irrigation channels. K, isopatches and flow lines. L, exploratory test pits. LL, exploratory boreholes. M, water flow and quality monitoring stations. N, piezometric level measurement.

The isopatches indicate that the Utrillas facies substrate discharges underground into the Quaternary lagoon aquitard, via small peripheral springs, some of which are more or less ferruginous (see Figure 7).

4.2.3. The Hydrogeological Behavior of the Majallana Stream

The Majallana stream crosses and feeds the Calatañazor wetland and its associated aquifer; its catchment area is around 3 km^2 and comprises Cretaceous marl and limestone soils with low permeability, located in the Utrillas area. However, this stream originates in an elongated upstream valley of almost 24 km^2, with very flat, gentle relief that extends across the calcareous moorland and the Fuentona recharge area. In reality, it is a dry valley where runoff seeps away, and water rarely reaches the Dehesa; when it does, it could be described as exceptional. However, during very rainy periods—though not exceptional ones—at the limestone-marl contact within the Las Peñuelas karst amphitheater, which lies one kilometer upstream from the start of the Dehesa, a torrent of crystal-clear water flows from the gravel of the dry stream bed at a rate of up to around 100 L/s, as we have observed on several occasions. At such times, the stream carries a great deal of water and floods the reservoir.

However, under normal conditions and during low-water periods, this channel is dry, and the stream originates further downstream at a permanent spring known as 'Ojo', with an average flow of around 2 L/s. This spring is actually the confluence of several drainage ditches from the surrounding farmland, which drain the sands of the Utrillas. This spring appears to lie at the interface between the Utrillas and Holocene or Pleistocene lacustrine clays. The Dehesa begins here, and relies on the stream, which carries water permanently to irrigate the meadows, where the water table remains high. The stream collects water from dozens of small springs and sources that rise from the Utrillas or from drainage ditches on the Dehesa plain itself.

The stream crossed the road with a flow of around 2 L/s during the dry month of April 2023 and fed the Cañaveral area, which is considered a zone of preferential evapotranspiration. It then exited this area via the reservoir's outlet at a flow rate of around 1.5 L/s, as measured in April 2023. The stream then enters a narrow valley, and at its exit, just before it joins the Avion, it carried more than 4 L/s (April 2023). In other words, it gains about 2.5 L/s in this narrow stretch. The stream is fed by discharges from the Cretaceous limestone aquifers intercalated between marl layers that extend down to the stream, and from the tuff terrace of the River Avión, which can also be considered an aquifer. Hence, this section of the stream is a net gainer, and a considerable amount of water originates here even at low water levels. We could say that this stream has its own flow in its lower reaches, making it independent of the lagoon's outflow. We say this because, if the lagoon's outflow dries up due to evaporation or evapotranspiration—whether or not the lagoon has recovered—, its impact on the stream downstream of the lagoon is, or would be, minimal.

4.2.4. Water Balance

The basic concept of the water balance is that the change in storage volume in a peat bog and associated sediments, such as those at Calatañazor, over a given time period is determined by the difference between the inflow and outflow of water during that period. The lagoon peat deposit forms a layer no more than 5 or 10 m thick that fills the bottom of the Calatañazor marsh and pastureland, covering an area of around 56 hectares. The following qualitative water balance can be established for it (indicated by Equation (1)):

$$\Delta A = P + ESE + FSUBE - ET - ESS - FSUBS \quad (1)$$

where

ΔA: Storage variation. This considers all reservoirs within the peatland and associated sediments: within the peatland itself, as reflected by water-table variations; and in inland lagoons.

P: Rainfall and snowfall falling directly onto the surface of the aquitard.

ESE: Surface runoff from the Majallana stream and the outskirts of the lagoon basin, which may seep into the water table.

FSUBE: Underground or subsurface inflow. Underground inflows from the base and sides through the sediments of the Utrillas subsoil which, although they do not have a significant surface catchment area (less than 2 km^2), contribute small streams that originate from springs and seeps in the Utrillas area on the outskirts, sometimes carrying iron-rich water. There may also be underground inflows not visible from the bottom which, whilst small, probably help to regulate the flow of the water table.

ET: Evapotranspiration. This is the most significant water loss from peatlands in the annual water balance, particularly during the summer. It is difficult to measure. In our case, it would refer to evapotranspiration in the Dehesa, the reed bed and the surrounding crops, which draw water from the water table.

ESS: Surface runoff leaving the peat bog, whether via natural channels, artificial drains, lagoon outflows, etc. In our case, this would be the surface drainage from the outlet stream downstream of Cañaveral, which, as explained earlier, almost never dries up.

FSUBS: Underground and subsurface outflow. There do not appear to be any underground outlets in the area of the outfall; if the flow increases, it is in the area where water discharges from the Cretaceous limestone or the tuff terrace shortly before its confluence with the Avión River, as mentioned, and these are excluded from the peatland's water balance calculations.

Establishing a quantitative water balance for the system from these individual components is particularly difficult. Therefore, we chose to assess the actual integrated response of the water balance by monitoring variations in groundwater level and changes in the extent of the lagoon and peatland water surface using repeated drone surveys.Groundwater level fluctuations were measured over a two-year period (from May 2023 to May 2025) at two piezometers located in the reed bed and the pastureland. This variation in the groundwater level is what results in a change in storage, depending on inflows and outflows. Accordingly, both piezometers show fluctuations that are more or less parallel and closely linked to rainfall (Figure 8). The water table fluctuates between 0 and 1 m in depth. Thus, there is a saturation equilibrium in the lagoon and peatland deposits, which keeps the water table permanently at a depth of less than 1 m throughout the reed bed and pasture.

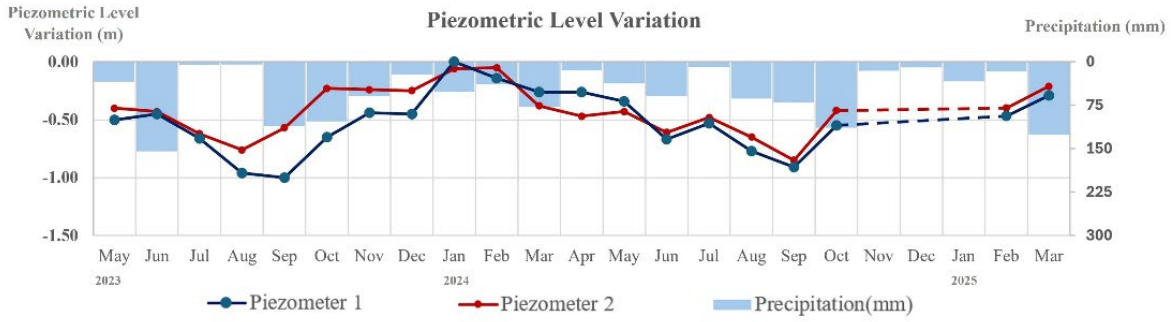


Figure 8. Variation in the piezometric level within the peat bog (piezometer 1 in the reed bed and piezometer 2 in the Dehesa), demonstrating its coupling with rainfall and an overall fluctuation of 1 m (STMA data). Monthly precipitation records from the nearby Soria Weather Station were retrieved from publicly available datasets provided by AEMET.

4.2.5. Hydrogeochemical Characteristics

Six water samples were taken for chemical analysis with the following objectives: (1) To determine the composition of the water within the peat aquifer using samples from boreholes (S1 and S2). (2) To determine the composition of the Majallana stream at its source at the Ojo spring, originating from the Utrillas facies (M3), at an intermediate section (M4) and at its exit from the system before flowing into the Avión River (M1). (3) To determine the composition of small local and short-flow springs from the Cretaceous (M2). The results are shown in Table 1.

Table 1. Analytical results for samples: S1 and S2: peat aquifer, with samples from boreholes. M1: Majallana stream at its exit from the system before flowing into the River Avión. M2: Small springs with localized, short-lived flows from the Cretaceous. M3: Spring of the Majallana stream originating from the Utrillas facies. M4: Majallana stream in a middle section.

Parameter (mg/L)	M1	M2	M3	M4	S1	S2
Bromides	0.03 ± 0.01	0.02 ± 0.01	<0.01	<0.01	0.02 ± 0.01	0.02 ± 0.01
Chlorides	4.9 ± 0.3	2.4 ± 0.1	3.3 ± 0.2	4.36 ± 0.3	0.145 ± 0.007	4.6 ± 0.3
Fluorides	0.137 ± 0.007	0.093 ± 0.005	0.104 ± 0.005	0.128 ± 0.006	0.145 ± 0.007	0.122 ± 0.006
Nitrates	5.1 ± 0.3	30 ± 2	7.2 ± 0.4	4.9 ± 0.2	0.71 ± 0.04	0.32 ± 0.02
Nitrites	0.06 ± 0.01	<0.01	0.11 ± 0.01	2.3 ± 0.2	<0.01	<0.01
Sulphates	22 ± 2	16 ± 2	11 ± 1	16 ± 2	9 ± 1	11 ± 1
Bicarbonates	290 ± 22	259 ± 19	300 ± 23	266 ± 20	199 ± 15	187 ± 14
Calcium	105 ± 11	97 ± 10	100 ± 10	92 ± 9	53 ± 5	58 ± 6
Magnesium	4.9 ± 0.5	6.7 ± 0.7	5.8 ± 0.6	4.5 ± 0.5	2.0 ± 0.2	2.5 ± 0.3
Sodium	3.3 ± 0.3	2.1 ± 0.2	2.3 ± 0.2	3.7 ± 0.4	2.7 ± 0.3	2.1 ± 0.2
Potassium	8.7 ± 0.9	1.5 ± 0.2	2.1 ± 0.2	9.1 ± 0.9	16 ± 2	11 ± 1

Figure 9 shows the Piper diagram, which reveals that the dominant hydrogeochemical facies is calcium bicarbonate in all cases, that the stream water (mainly influenced by the Utrillas) is quite similar to Cretaceous water (M2), and that the two peat water samples are very similar. However, peat-bog water is less mineralized than the rest. This is evident from in situ measurements of spring and irrigation-channel water conductivity, which varies between 500 and 618 µs/cm, regardless of whether it originates from the Utrillas or the Cretaceous. These values are higher than those of the peatland groundwater, which is around 350 µs/cm.

Although the iron content has not been determined, the ferruginous nature of the groundwater originating from the Utrillas is evident, in both the small springs in the Enebral area and the drainage ditches throughout the Dehesa. This is not the case with the Cretaceous springs.

According to measurements taken at boreholes S1 and S2, which have penetrated the peat layers, the pH remains at 7.3; therefore, the water is not acidic and does not require treatment in the lagoon or at the outfall. This is undoubtedly because, in addition to the sand from the Utrillas, the limestone debris from the slopes influences the nature of the sediments trapped by the lagoon, thereby neutralizing the acidity.

On the other hand, it appears that the peat bog has a self-purifying effect on the water passing through it, as levels of almost all ions—with the exception of potassium—decrease, and there is evidence of denitrification and a reduction in sulphate levels.

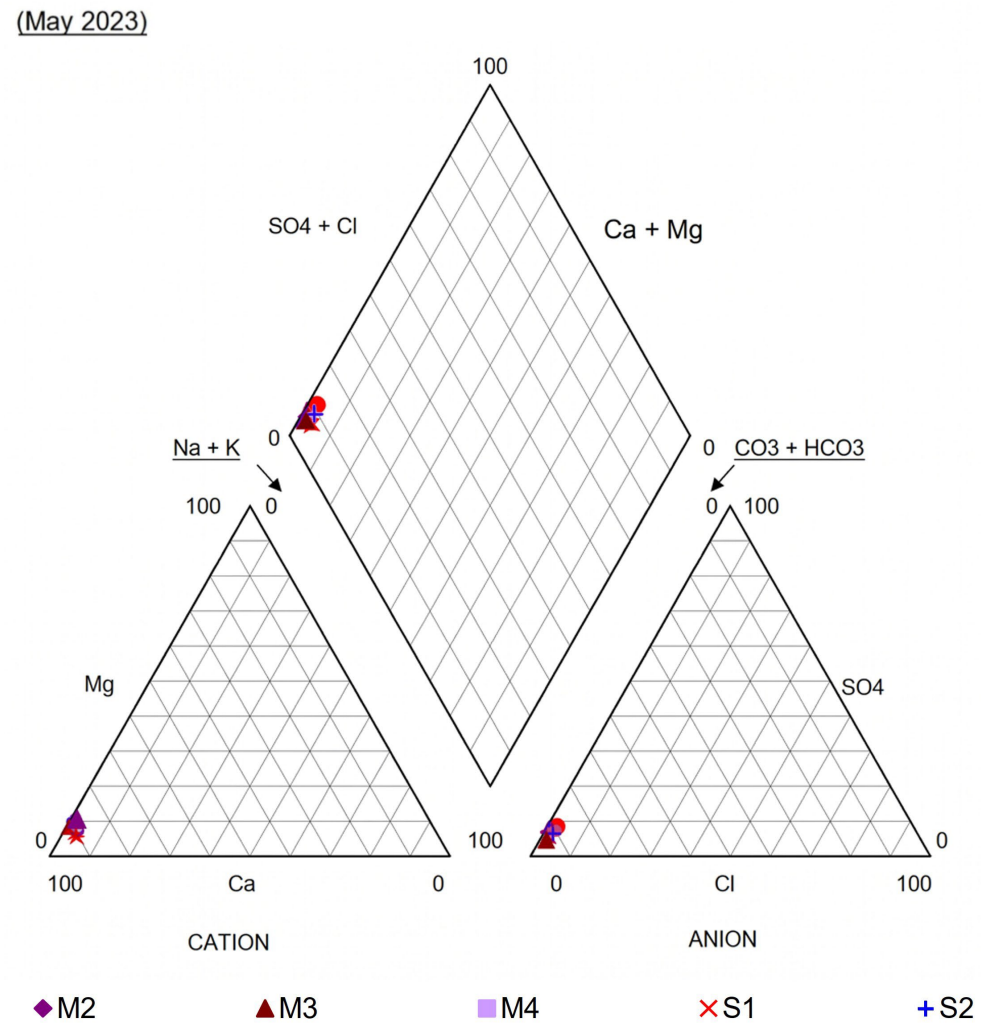


Figure 9. Piper diagram of the groundwater in the Quaternary aquifer and the substrate of Calatañazor Lagoon.

5. Discussion

5.1. Origin and Evolution of Calatañazor Lagoon

The managers of these areas have recognized the need to consider the past, as best practice in the nature reserve management recommends including this information in management plans. It is therefore important to understand this lake's origin and evolution, which has followed the typical stages seen in peat lakes. Based on the interpretation of the existing surface geological formations, we propose the following evolutionary model, summarized in Figure 10.

Phase 1: Blockage of a side valley by a tuff terrace on the River Avión

The River Avión, which rises from the large karst spring of La Fuentona (average flow of 1000 L/s), likely formed a large tuff terrace during the Middle Pleistocene, which closed off the valley of the Majallana side stream and tributary, acting as a dam. This resulted in a lagoon formed by lateral closure, which would have occupied the area covered by lacustrine sediments shown in Figure 6. It would have been a small open-water lake where detrital materials (sand, silt, clay) carried by the tributaries (Ayo Majallana) and peripheral runoff would have accumulated. It cannot be ruled out that the overflow spring at the head of the stream played a role in the formation of the tuff terrace if it was more active at that time, but this is not certain.

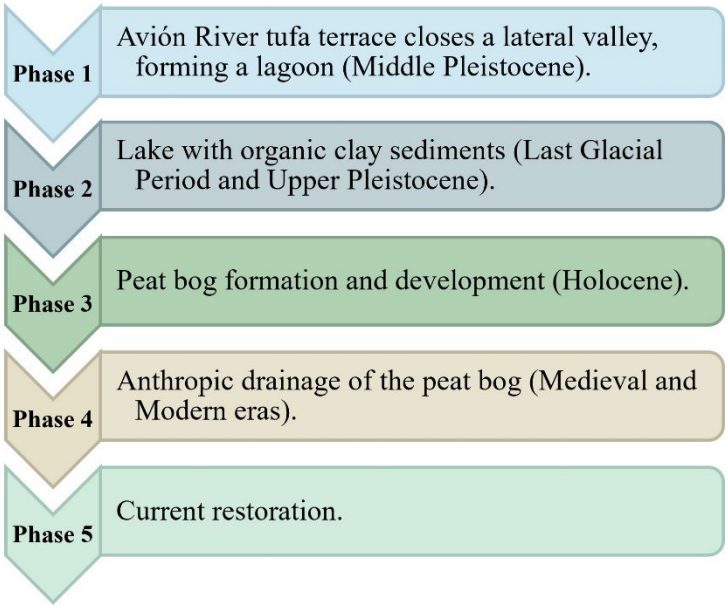


Figure 10. Stages of development in the formation of the Calatañazor peat bog.

Phase 2. Lake with organic clay sediments (Last Glacial Period and Upper Pleistocene)

In this lagoon, there was significant deposition of gray clays rich in organic matter on a substrate consisting mainly of silica from the Utrillas facies. This occurred before 7590 BP in the Upper Pleistocene/Holocene, which is when peat formation would have begun. The cold conditions prevented significant development of vegetation and peat.

Phase 3. Lowland marsh phase (topogenic peat bog): (Holocene)

Subsequently, a sedimentary terrace formed around the lake, which was rapidly colonized by hygrophilous plants: common reed and sedges.

The River Avión pushes and forces the course of the drainage stream (Ayo Majallana) to cut between the slope of the Cretaceous substrate and the tuff terrace, as we see it today, perhaps deepened further by anthropogenic drainage works.

The tufa-lined lagoon gradually becomes silted up, and organic sedimentation begins to dominate as a belt of marsh vegetation colonizes the area, where decomposition is incomplete. The water surface area gradually shrinks. Peripheral water inflows mineralize the environment. This clay-filling of peat is complete, as evidenced by a thick peat that extends continuously over the gray clays across most of the wetland and pastureland, except, it seems, at its headwaters. This peatland ecosystem emerged between 7590 BP and 5800 BP, mainly during the first third of the Holocene. The peat layer reaches a maximum thickness of 8 m in the area near the outlet at Carrizal, indicating that this area was the most active.

During this period, there was a continuous accumulation of organic matter. The limited water circulation through the body of a peat bog and the fact that this environment was almost entirely waterlogged created an anoxic environment that inhibited the bacterial activity responsible for the decomposition of organic matter, facilitating a process in which productivity exceeded decomposition in the annual balance.

We believe this is a good example of the formation of muddy sediments in an area where rainfall is not abundant, but where a lagoon has formed due to a natural barrier of tuff, in which water from river courses accumulates, along with surface runoff and groundwater discharge.

The key to the preserved organic matter remaining intact for so long lies not in the local climate's temperature regime but in a hydrological factor: the permanent availability of water, which, in the case of Calatañazor, was not due to frequent local rainfall, but rather to

poor drainage conditions, as it was a lagoon enclosed by a natural tuff dam, supplemented by inflows from adjacent areas, as mentioned above. The ecosystem's hydrological self-regulation capacity has allowed sustained development over time, overcoming the effects of severe droughts or excessive rainfall. This has been the key to the Calatañazor peat bog remaining largely undisturbed until historical times. Indeed, the persistence of the water table near the surface (without leading to waterlogging) has favored the ecosystem's stability and development and prevented the growth of species not adapted to the bog's specific environment. Furthermore, the saturation level of a lagoon- and valley-bottom peat bog like this is even more stable and closer to the surface than in an elevated peat bog, because stagnation of its surface and underground inflows makes it more stable over time.

As is well known, peat formation began only during the period of definitive warming—globally referred to as the post-glacial period or Holocene, which began 10,000 years ago. The early phases of this period (the Pre-Boreal up to 8700 years ago and the Boreal up to 7000 years ago) were still poor in peat, characterized by a fairly dry climate and fairly permanent anticyclonic conditions [7]. Therefore, with a few exceptions, peat did not develop extensively during this period. Conversely, peat formation became widespread in the subsequent period known as the Atlantic, when rainfall was abundant and average temperatures were slightly higher than today. However, the relationship between sediment type and depositional period is not generally or clearly established. This may mean that a given climatic phase does not systematically correspond to a dominant deposit. Climate is not the sole factor that controls deposition. Other factors that shape sedimentation include: basin type, catchment area nature and dimensions outlet elevation, and the importance and nature of tributaries.

This is the case with the Calatañazor system, which is a valley-floor peatland complex associated with a tufa-lined lagoon, fed both by underground inflows and by a surface watercourse that originated partly outside the peatland environment. In Calatañazor Lagoon, as mentioned, most of the peat formation occurred between 7590 BP and 5800 BP; however, in this case there is no direct correlation between climate and peat formation, as water was always available due to accumulation in the lagoon basin. This is why understanding the functioning of the peatland at the ecosystem level largely involves understanding the complexity of flow movements in these wetlands, variations in the water table and interactions with the surrounding environment, mediated through water, which determine the local biogeochemical characteristics.

Phase 4: Anthropogenic influence

Paradoxically, peatlands are extremely vulnerable to human activity. The most frequent and severe impact results from the construction of drainage systems, whether for the purpose of facilitating peat extraction, building infrastructure, or changing land use. Implementing drains immediately lowers the water table within the peatland and increases oxygen availability in the affected, thereby undermining the fundamental condition that ensured the ecosystem's stability.

Drainage works were carried out in the Calatañazor lagoon to reclaim land for agriculture and to use the Dehesa for livestock, most likely dating back to very ancient times (the Middle Ages, or perhaps even Roman times). Although, as mentioned, we have a more recent example: in the 1940s, for instance, the irrigation channels were deepened to lower the water table and thus open up new land for cultivation. Fortunately, these were not dug more than two meters deep in the area of the outlet stream, and as the peat layer is thick, it has remained below the water table for the most part. Nor was there any interest in digging much deeper, as it was also important to keep the moisture close by for the meadows and farmland.

This drainage situation triggers a series of slow, continuous processes over time: first, the initiation of aerobic decomposition. This is why arable soil formed throughout the area, including the pastureland, where drainage works were also carried out. It is worth noting that the topsoil, almost 1 m thick, is actually the drained area of the original peat bog. This thickness corresponds to the minimum depth to which the water table currently fluctuates.

5.2. Environmental Improvements Undertaken: Rehabilitation of a Small Pond and Restoration of the Peat Bog

5.2.1. Restoration and Conservation Objectives for the Peat Bog

The university's scientific knowledge about this site has been shared through exchanges and meetings with environmental authorities and considered for incorporation into conservation plans. Furthermore, the traditional uses of the site have been analyzed, providing an opportunity to discuss restoration plans with the local population. These improvements advocated by environmental managers aim to establish the following feasible restoration and conservation objectives for the Dehesa de Calatañazor peat bog: 1. Firstly, the intention is to protect the peat bog in its current state, preserving the existing reed bed that has been achieved through active management in recent years. 2. The complete restoration of this peat bog, understood as returning it to its original state unaffected by human activity, by converting the cattle pasture in the upper half of the bog into a reed bed, does not appear to be feasible:

- Firstly, because this pastureland is currently in use and has been fully integrated into the landscape of El Sabinar since ancient times. The pastureland contains a watercourse (the Majallana stream) that has served as a drainage channel since ancient times, as evidenced by clayey topsoil layer up to one meter thick, with little peat. In other words, the peat bog has been subject to human activity for centuries and millennia, and this has irreversibly destroyed the upper part of the previous peat layer, with other types of material having settled in its place.
- Secondly, as is well known, the most important restoration technique is re-wetting, that is, raising the average annual water table to approximately the level of the peat surface. However, in this case, the top layer is no longer peat, so raising the water table by one meter by blocking the drains in the reed bed makes no sense. This restoration project will therefore need to be compatible with the traditional use of the pastureland for livestock, which is what has been done up to now.
- Thirdly, the creation of a small, shallow pond within the reed bed to provide a visible body of water that draws attention to the presence and importance of a peat bog which currently goes unnoticed. The aim is to simulate a final stage of silting up, as is also currently occurring during high water. This will also attract birds and encourage them to nest there.

5.2.2. Estimation of Evaporation from the Lagoon as a Component of the New Water Balance

This single-pond solution was not selected from the outset and was discussed alongside other alternatives involving multiple ponds, as will be seen later. However, as it emerged as the most suitable option, the rate of evaporation was estimated to ensure it was compatible with the available water supply.

Indeed, with the restoration of part of the lagoon, by excavating below the water table, the aquifer will be exposed in the form of a window, like a free-surface opening where direct evaporation will occur. This is a new water outlet that the ecosystem did not previously have. To determine the size of this new lagoon, the approach has been reversed: that is, calculating the evaporation that will occur based on its surface area to ensure the water

balance is not disrupted. For this purpose, direct evaporation data from the Soria station—located at an altitude of approximately 1110 m and less than 30 km away, with climatic characteristics similar to this area—has been used. At the Soria meteorological station, we measured evaporation directly using a Piché evaporimeter and evaporation pans. The data from these instruments are used in the present study. Figure 11 presents the average annual evaporation by month from a historical time series spanning more than 40 years, totaling 1081 mm.

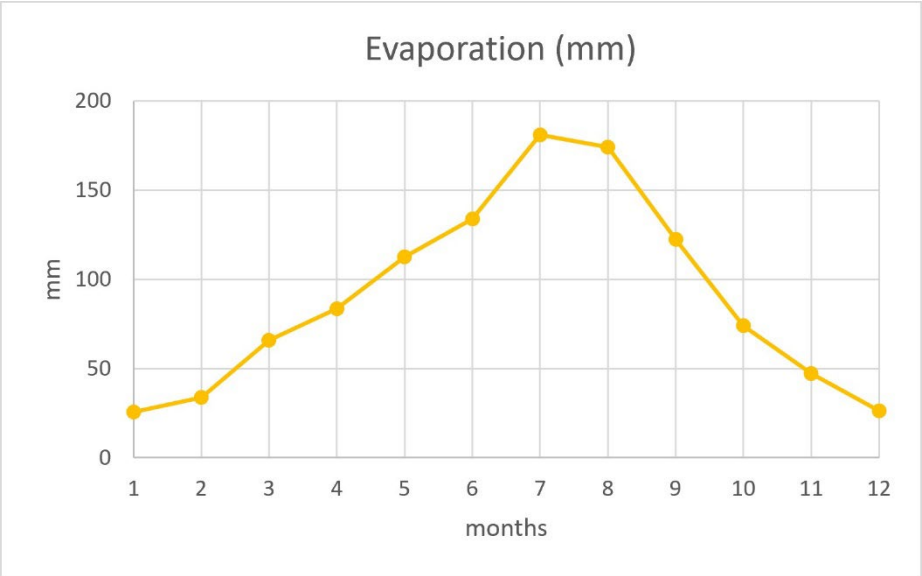


Figure 11. Mean monthly evaporation for a representative year at the Soria urban weather station (months numbered from 1 = January to 12 = December). Plotted by the authors using publicly available meteorological records provided by the Spanish State Meteorological Agency (AEMET).

Therefore, as the planned lagoon has a surface area of 7000 m^2, this would result in a new outflow from the aquifer system via direct evaporation equivalent to a continuous flow of 0.238 L/s, which appears to be manageable. In reality, this would involve adding the difference between the direct evaporation from the planned lagoon and the evapotranspiration of the phreatophytes that were previously present, as well as comparing this with agricultural cultivation across the 10 ha and taking into account the final surface area of the lagoon, which currently stands at 7000 m^2.

5.2.3. The Peatland Restoration Process and Work Carried out

From a practical point of view, restoring the peatland has not been straightforward, given the importance of, and the high dependence on, the income generated by what might be described as traditional uses of the pastureland over the last century. On the one hand, livestock farming requires that the pastures be accessible to livestock (which is why there are small drains in the pasture); on the other hand, local farmers' incomes depend on these plots.

It has been a process of negotiation involving a series of small, successive steps. It is a fine example of reconciling differing interests and taking progressive action based on consensus. Given these constraints, and bearing in mind that the existing road and the interests of local farmers must not be affected, work has been carried out to restore part of the old lagoon, thereby improving the biodiversity of the nature reserve and seeking to preserve a sample of the peat formation processes that had, in practice, disappeared from the surface of the land.

Initially, the Environment Department identified an area of 10.09 ha as the most prone to flooding in measurements carried out as part of the nature reserve's management. Discussions with the two local authorities, supported by the nature reserve's board of trustees, which has consistently backed the lagoon restoration project, secured its exclusion from agricultural use (Figure 12). Thus, in November 2011, a request was made to the Directorate-General for Common Agricultural Policy of the Regional Government of Castile and León to change the SIGPAC classification of that area from arable land to water body. Furthermore, it was excluded from annual agricultural use.

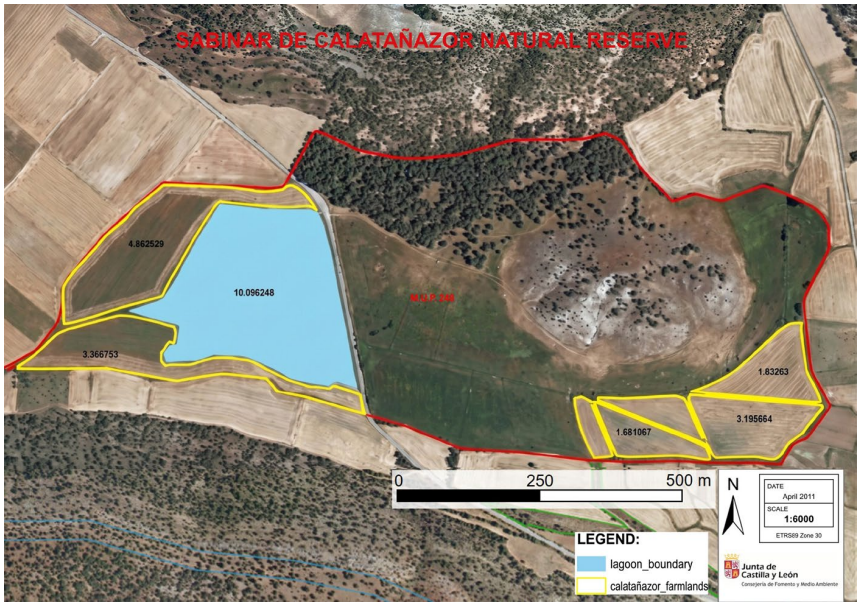


Figure 12. Area where STMA has been successfully excluded from agricultural cultivation.

Since then, the land has made a remarkable recovery: soil moisture levels have improved, the area has rapidly become overgrown with protective reeds, and it has become a nesting site and refuge for the marsh harrier and other species (see Figure 12). The loss of income and crops was accepted, and a substantial improvement was achieved for the nature reserve (see Figure 13).



Figure 13. During the winter, it is evident that arable land recovers quickly just a few years after cultivation has ceased. This corresponds to the area most prone to flooding and most difficult to

cultivate in a rainy year. A greater amount of reed is visible in the drainage channels, which impedes and reduces their drainage function and promotes natural soil moisture retention. It is important to note the proximity of the road and the somewhat waterlogged crops in the western part to better understand the initial conditions.

From this point onwards, efforts were made to move forward with a second phase, involving the involvement and collaboration of the various authorities to carry out a partial restoration of the lagoon. To this end, a series of meetings were organized by the Department of the Environment of the Regional Government of Castile and León and local authorities, together with the Duero River Basin Authority and the Government Sub-delegation itself, to determine how best to approach the project. The difficulty lay, on the one hand, in securing funding and, above all, in clearly defining the objective so as not to cause harm to the surrounding farmers and the road itself, whilst achieving the conservation goals. Various well-intentioned initial proposals were considered, such as closing off the Majallana stream with a small dyke, and closing the drains and several ponds; however, none of these had been sufficiently developed, and there was a lack of funding and, above all, of scientific and technical support, as well as support from the landowners, who were skeptical and fearful of the potential harm the project might cause them. These included a likely rise in water levels, the possibility that the tail of the backwater might affect the road, the crops themselves and the pastureland by raising the water level, and even the loss of water and moisture from the valley as a result of the excavation. Other drawbacks included the difficulty in managing the site during floods due to the nature of the material, and concerns among conservationists about the use of machinery and civil engineering works, given their potential impact on the recently restored area and, in particular, on amphibians.

An opportunity has arisen through the Recovery, Transformation and Resilience Plan, funded by the European Union through the Next Generation EU Recovery and Resilience Facility. This initiative is a wetland biodiversity conservation project that will be implemented through the Regional Ministry of the Environment, Housing and Spatial Planning of the Regional Government of Castile and León. The Natural Heritage Foundation will carry out the specific implementation, enabling us to conduct the necessary preliminary studies with the university. This will allow us to approach the restoration project with greater certainty and a stronger foundation, while also helping resolve any existing doubts. With the authorizations of the Calatañazor Town Council, the Aldehuela de Calatañazor Local Authority, the Duero River Basin Authority and the Nature Reserve Board, and following discussions with AMAR (the Friends of Mammals, Amphibians and Reptiles of Soria) and others, the project was approved by the Regional Ministry of the Environment and began implementation through the public company Tragsa in late summer 2025.

The initial proposal included options such as several small pools between the drains. In the end, the decision was made to create a single shallow pond in a central position at the lowest elevation (997.4 m), with the aim of separating it from the main stream, the high-voltage power line, the road and the worksite to minimize mutual interactions, whilst seeking to collect water and protect the reed belt that has formed over recent years (Figure 14). Being separated from the stream prevents contamination and ensures it does not act as a settling pond that fills up quickly.

A kidney-shaped design was chosen and positioned to intersect the two central drains, including their confluence, as a means of retaining groundwater, which would be filtered water. Its dimensions were not to exceed 10% of the 10-hectare floodplain. (maximum size of 1 ha) and its depth should be between 30 and 100 cm, so as to affect only the surface soils altered by agriculture and not reach the peat layer or the impermeable layers, and to fall within the ranges of the piezometric data, all in accordance with previous studies carried out. This ensures a small water window in summer (Figure 15).

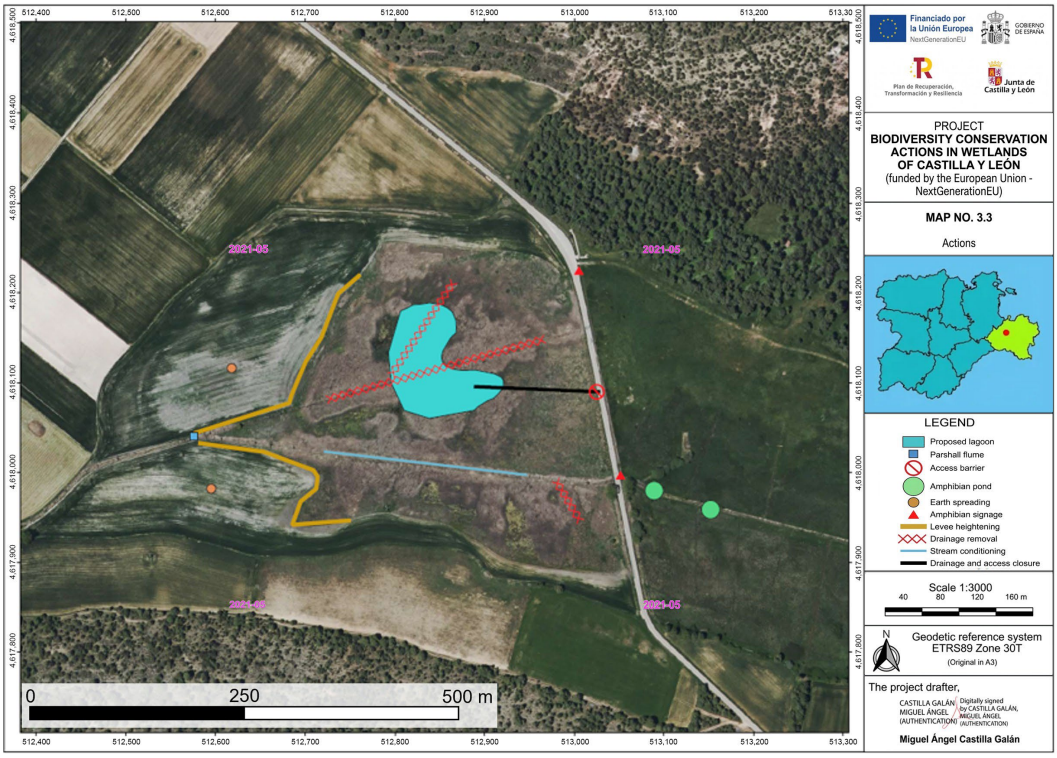


Figure 14. Project action plan. It is also worth noting the spread of the reed, which at that time would have covered 35% of the area. By the time the project was carried out, it had already covered 100% of the area.



Figure 15. (**Left**) Overview of work on the lagoon and storage of excavated material on the worksite. (**Right**) Excavation work carried out and exposure of the water table.

One notable measure involves using the excavated soil to raise the level of nearby agricultural land that may be affected by water. This measure, which retains the original name of 'mound raising', was improved by changing the approach from a linear to a surface-based method.

Other measures carried out at the same time included plugging the drains and slightly raising the cross-section of the Majallana stream using the same excavated material, specifically in the section running alongside the lagoon, to slow the flow of water. All these measures are easy to manage and can be adapted without issues regarding reversibility. Even the lagoon itself, with expected reed growth, will provide biomass that can activate the peat bog and may silt it up within a few years.

The plan included a small access path, which would subsequently be closed off, and a few small ponds for amphibians on the other side of the stream, designed to channel and reduce the movement of amphibians and their mortality on the road. At the same time, these would serve as natural water sources for biodiversity and livestock on the juniper side. A flow measurement system would also be installed at the stream's outlet for hydrological monitoring (Figure 14).

As of the date of this report, it should be noted that 1200 m^3 of reed biomass have been removed and 3600 m^3 of topsoil have been excavated; this material has been deposited on adjacent agricultural land prone to flooding to raise its level. This represents 65% of the planned work, and in terms of surface area, we are looking at around 7000 m^2, which equates to an average excavation depth of 0.51 m (Figure 15). The result following the rains of January–February 2026 is shown in Figure 16.



Figure 16. A shallow lagoon restored in a central position within the reed bed.

5.2.4. Monitoring and Evaluation Techniques for Restoration Measures

With restoration work on the peatland recently completed, and although this is a relatively 'intact' peatland, monitoring will focus on peat erosion/accumulation, stream flow, water table depth, water quality, vegetation, fauna, and flora. A standard 'before and after' monitoring approach is used in all studies, collecting baseline data prior to the start of restoration work and maintaining a control site in an unrestored condition, so that the monitoring results from the sites undergoing restoration can be compared with the untreated site, to account for any external factors.

From a purely hydrological perspective, it will be necessary to monitor the results and effectiveness of the water retention measures implemented, and to what extent waterlogging is increasing, whilst observing the evolution of the surrounding vegetation towards aquatic and hydrophytic communities and the consequent expansion of these habitats.

To monitor hydrometry and hydrochemistry at the inlet, within, and at the outlet of the peat bog, periodic manual measurements of water level and/or flow rate will be taken at selected points: in the lagoon, in the tributary stream at the road bridge, and in the outlet river before it enters the narrow valley, with measurements taken periodically, during high water and low water periods. Monitoring the river flow downstream throughout the system facilitates the assessment of the impact of evaporation from the lagoon on the system's water balance.

Although no major problems are expected, as there is no intensive livestock farming in the upper catchment area, water quality and temperature measurements will also be taken at these sites from time to time. The water table will be measured manually at the two piezometers, which will help us to understand how it evolves over time and to what extent it changes as a result of the new restoration work. Changes in the level measured at the Dehesa piezometer will tell us whether the rise in the water table on the other side of the road also affects the Dehesa, and to what extent the road hinders this; the surface water level will also be observed in the vicinity of the road on both sides.

6. Conclusions

Many peat bogs in the Mediterranean region are intrinsically linked to karst geomorphology and result from the filling of lakes formed by tuffaceous river barriers. The Calatañazor peat bog, in particular, originated when an extensive terrace of calcareous tuffs from the Avión River laterally closed a valley during the Pleistocene. This 'natural dam' created an endorheic basin that allowed the transition from an open-water lake (lacustrine clay phase) to a topogenic peat bog ecosystem. C-14 dating has established that the period of greatest peat formation activity occurred in the early to middle Holocene (between 7590 and 5800 years BP), reaching a maximum thickness of up to 8 meters.

As a low-energy system dependent on groundwater (from the Utrillas aquifer and limestone), it is far more resilient to climate change than peatlands that rely solely on rainfall (ombrotrophic), which is why it has survived to the present day. Permanent water saturation has preserved this organic carbon reservoir over millennia by creating an anoxic environment that inhibits bacterial decomposition, regardless of external climatic fluctuations. In the current context of drought, demonstrating that there are hydrogeological refuges that remain stable thanks to deep geology is a topic we believe to be of the utmost scientific relevance.

The hydrogeological model consists of a lagoon-type aquitard supported by the sands of the Utrillas Facies. Hydrochemically, the waters are calcium bicarbonate-rich with a neutral pH (7.3), defying the stereotype of acidic peatlands. It has been demonstrated that the peatland provides an ecosystem service of water quality regulation, acting as a biological filter that significantly reduces the concentration of nitrates and sulphates through natural denitrification processes, thereby protecting the quality of the discharge into the River Avión.

Human intervention, particularly the deep drainage works carried out in the 1940s, disrupted the water balance by lowering the water table below the critical threshold. This triggered the aerobic decomposition of the upper peat, transforming it into a clayey 'topsoil' approximately one meter thick. This surface layer now acts as a seal that conceals the deep peat, but also limits the original wetland's capacity for self-regulation.

The most significant technical conclusion for conservation engineering is that restoration cannot fully return the site to its pristine state. Full re-wetting would flood the pastureland, destroy traditional livestock farming and jeopardize the survival of the white juniper grove, whose unique specimens depend on a specific balance of moisture and nutrients. Therefore, creating a shallow 7000 m^2 pond and blocking drains is the optimal solution: it restores the visible water surface, keeps the water table within a safe range for tree vegetation, and is hydrologically feasible, with minimal evaporation loss relative to the system's inflows. It has been verified that the upstream pond can be flooded or restored without fear of drying out the downstream stream: the system has 'hydrological redundancy'. All of this is consistent with the restoration's aim of keeping the water table above −50 cm to prevent the oxidation of the peat, which is preserved as such; for if the level drops below

50–100 cm for a prolonged period, the peat will almost certainly oxidize and change from being a carbon sink to a source of emissions.

This case demonstrates that eco-hydrogeology is an indispensable tool for administrative decision-making. Collaboration between the University and official environmental managers has made it possible to transform a potential conflict between agriculture, livestock farming and conservation into a project funded by the European Union that safeguards the future of the peatland. It should be noted that this is the result of years of work involving many stakeholders and that it will continue with the hydrological and biological monitoring program launched in 2026, which will be key to assessing the recovery of biodiversity and the reactivation of carbon sequestration processes in this Mediterranean refuge.

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