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# The role of geologists in basin management: 100 years of experience from the Ebro river basin authority

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**Abstract:** The Ebro River Basin Authority (Confederación Hidrográfica del Ebro, CHE), with nearly a century of history, plays a key role in the integrated management of water in Spain's largest river basin. This work highlights the functions and contributions of geology professionals within the CHE's technical structure. These professionals are integrated into three of its four functional units: the Water Commissioner's Office, the Technical Directorate, and the Hydrological Planning Office. Geology has been a core consideration within the Authority since its foundation in 1926, particularly in relation to the construction of hydraulic works. Since the 1990s, geologists have assumed responsibility for key activities including hydrogeological mapping, groundwater body characterization, aquifer status assessment, groundwater modelling, monitoring of the hydraulic public domain, and geotechnical surveillance of dams and hydraulic infrastructures.

This article provides an overview of geological work within the CHE as an indispensable discipline for effective water management, underlining its strategic role in water planning, risk management, and the sustainability of both groundwater and surface water resources in the Ebro River Basin District.

**Key words:** Geology, River Basin Authorities, Hydrogeology, Geotechnical Engineering, Environmental Geology

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## 1. Introduction

The Ebro River Basin Authority (Confederación Hidrográfica del Ebro, CHE), a world pioneer in integrated water management, has played a key role in the hydraulic, social, and environmental development of its basin since its establishment on March 6, 1926.

The Ebro River Basin exhibits high geological variability (Figure 1), requiring a thorough understanding of the environment for the planning and management of water-related projects. This geological complexity directly influences groundwater availability, monitoring network design, and the technical assessment of water resources across the basin.

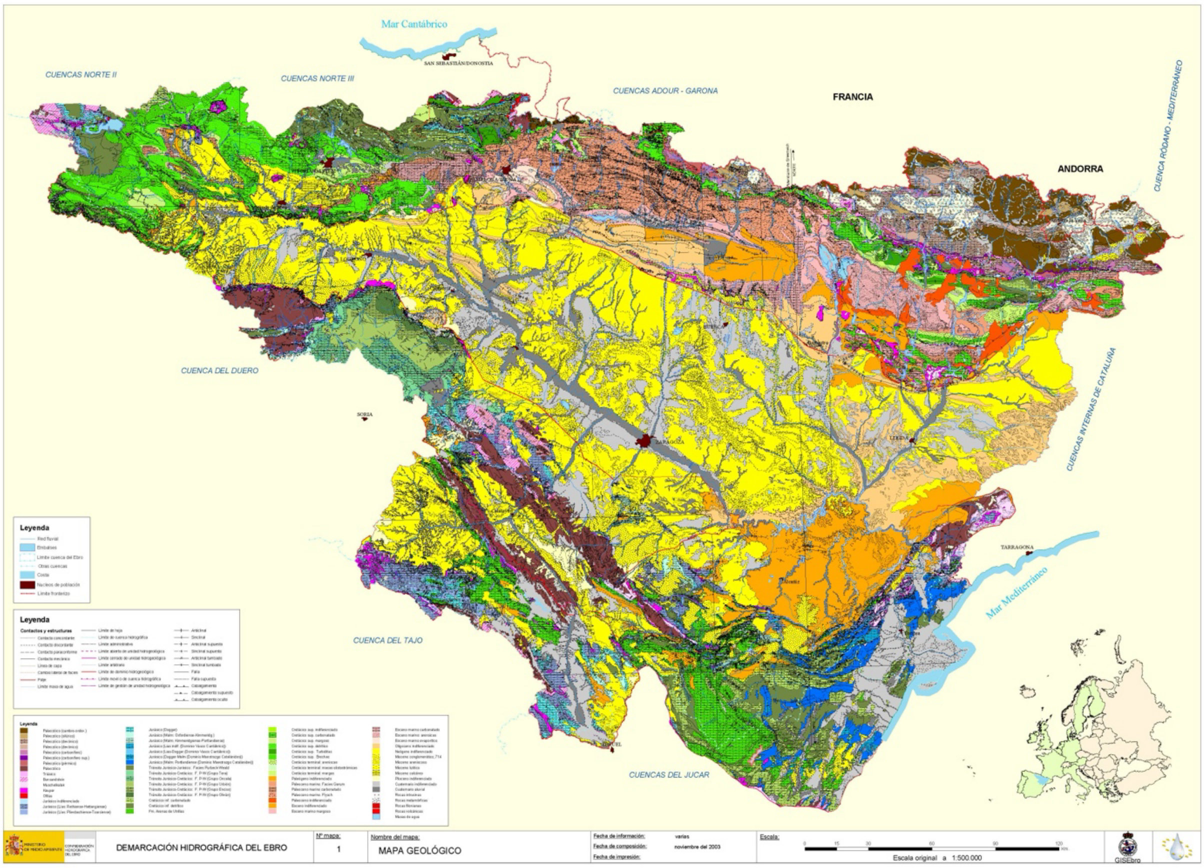


**Figure 1:** Geological map of the Ebro River Basin, showing the main lithological units and structural features of the region.

Over its one hundred years' history, the CHE's technical approach has evolved from the construction of large dams and canals toward a more complex, multidisciplinary management framework, in which environmental, hydrogeological, and territorial aspects play an increasingly significant role.

This evolution can be broadly understood in three stages. The early period (1926–1960) focused mainly on the construction of major hydraulic infrastructures, supported by geological and geotechnical investigations for dam siting. A second phase (1960–2000) saw the consolidation of basin-scale technical management and the progressive incorporation of hydrogeological knowledge. Finally, after the implementation of the European Water Framework Directive, basin management has increasingly relied on integrated environmental assessment, monitoring networks, and groundwater characterization, where geological expertise plays a key role.

In this context, geologists have been pivotal in the evolution of basin management. Their role has progressively broadened from a standard performance in ground technology-related sideworks to a more significant contribution, including groundwater assessment, monitoring networks, hydrogeological modelling, and a deep involvement in plannification and management decisions.

Geology has gained increasing importance within the CHE's core competencies, particularly after the 1985 Water Act recognized groundwater as part of the Hydraulic Public Domain (HPD). This legal framework led to the incorporation of geologists into the Authority from the late 1980s onwards. Today, these specialists perform key functions across several technical units of the organization. This article highlights the current contribution of geologists within the CHE through a selection of significant technical works carried out in recent years. The aim is to emphasize the geological perspective as an indispensable component of integrated water management, especially in the context of emerging challenges such as climate change, increasing pressure on groundwater resources, and the need for technically robust and environmentally sustainable solutions.

## 2. River Basin Authority

The inception of the CHE goes back to 1926. With this regard, it can be considered the very first river basin authority in the world [1; 2]. Promoted by Minister Rafael Benjumea and under the technical direction of Manuel Lorenzo Pardo, the CHE developed the General Plan for the Utilization of the Ebro (1927), which integrated river regulation, hydroelectric development, and territorial and economic considerations [3; 4].

The technical contribution of the Geological and Mining Institute of Spain (IGME) was paramount from the outset, providing key geological and geotechnical surveys for the siting and feasibility of major hydraulic infrastructures, particularly dams [5; 6].

**Tasks and Functions**

The CHE is part of the Spanish Central Administration and operates under the ministry for environmental matters—currently the Ministry for the Ecological Transition and the Demographic Challenge (MITECO). It is also the authority in charge of managing the Hydraulic Public Domain within the boundaries of the Ebro River Basin, the largest basin in the country.

The CHE's functions are established by the Consolidated Text of the Water Act (TRLA, Royal Legislative Decree 1/2001 [7]) and its regulatory framework, as well as by the EU Water Framework Directive (2000/60/EC) (WFD) [8]. Its duties include preparing river basin management plans, managing water resources—through "concessions" and "authorizations" (different type of permits), monitoring, control networks, and coordination with user associations, bringing everybody into alignment—and overseeing of projects and works of general interest, such as reservoirs and canals. All activities are carried out in accordance with the principles of coordination, participation, and shared responsibility among administrations, users, and society. Collegiate bodies, together with the commitment of CHE professionals, have been crucial to the Authority's success. This technical, participatory, and decentralized model, based on the river basin unit, has become a benchmark, progressively replicated in other Spanish river basins and recognized as a reference model in Europe and other countries.

As much as the institutional structure of the CHE is specific to Spain, several aspects of its experience are transferable to other European river basin administrations. These include the integration of geological expertise in groundwater body characterization, monitoring network design, abstraction control, and pressure assessment within the framework of the Water Framework Directive. The long-term building-up of hydrogeological knowledge within basin authorities provides a strong technical basis for adaptive water management under increasing climatic and anthropogenic pressures.

At the technical-operational level, the CHE manages systems such as Hydrological Automatic Information System (SAIH) and Automatic Water Quality Information System (SAICA), intended for hydrological monitoring and real-time reservoir management, aimed at preventing floods. From an environmental point of view, it implements, operates, and maintains monitoring networks for water bodies, as well as river restoration measures. Governance is guaranteed by "collegiate" (i.e. collective) bodies with participation from public administrations and users, which ensures transparency and alignment with European regulations. Furthermore, the CHE increasingly relies on digitalization, remote monitoring systems, georeferenced databases, and hydrological modelling as strategic tools for adaptive water management under climate change. [9, 10].

Within this institutional framework, geologists play both technical and decision-making roles. They carry out hydrogeological assessments supporting groundwater characterization, abstraction control, and the evaluation of pressures and impacts. In addition, several geologists occupy senior management positions within the River Basin Authority, including the Deputy Water Commissioner, the Head of the Hydrological Planning Office, and "area" (department) managers. Consequently, not only does geological expertise contribute to technical analysis but also helps out in administrative decision-making processes that affect basin management.

**2.1. Administrative Organization: A Brief Historical Overview**

As a public institution under its chairman or "president", CHE consists of four administrative units—the Water Commissioner's Office, the Technical Directorate, the General Secretariat, and the Hydrological Planning Office (Figure 2)— and functions by means of collegiate bodies, but for the President, a single-person managing body in itself. A careful governing system, proxy-based design, ensures a voice to all stakeholkders, covering ground at a state, region and users level [11].This structure, consolidated in the enactment of the 1985 Water Act, has evolved from its original form of a "Syndical Confederation of Users". Successive regulatory changes, including the 1934 Decree and the 1942 Order by which users' representation was ruled out, led to a redefinition of its functions and degree of autonomy [12].

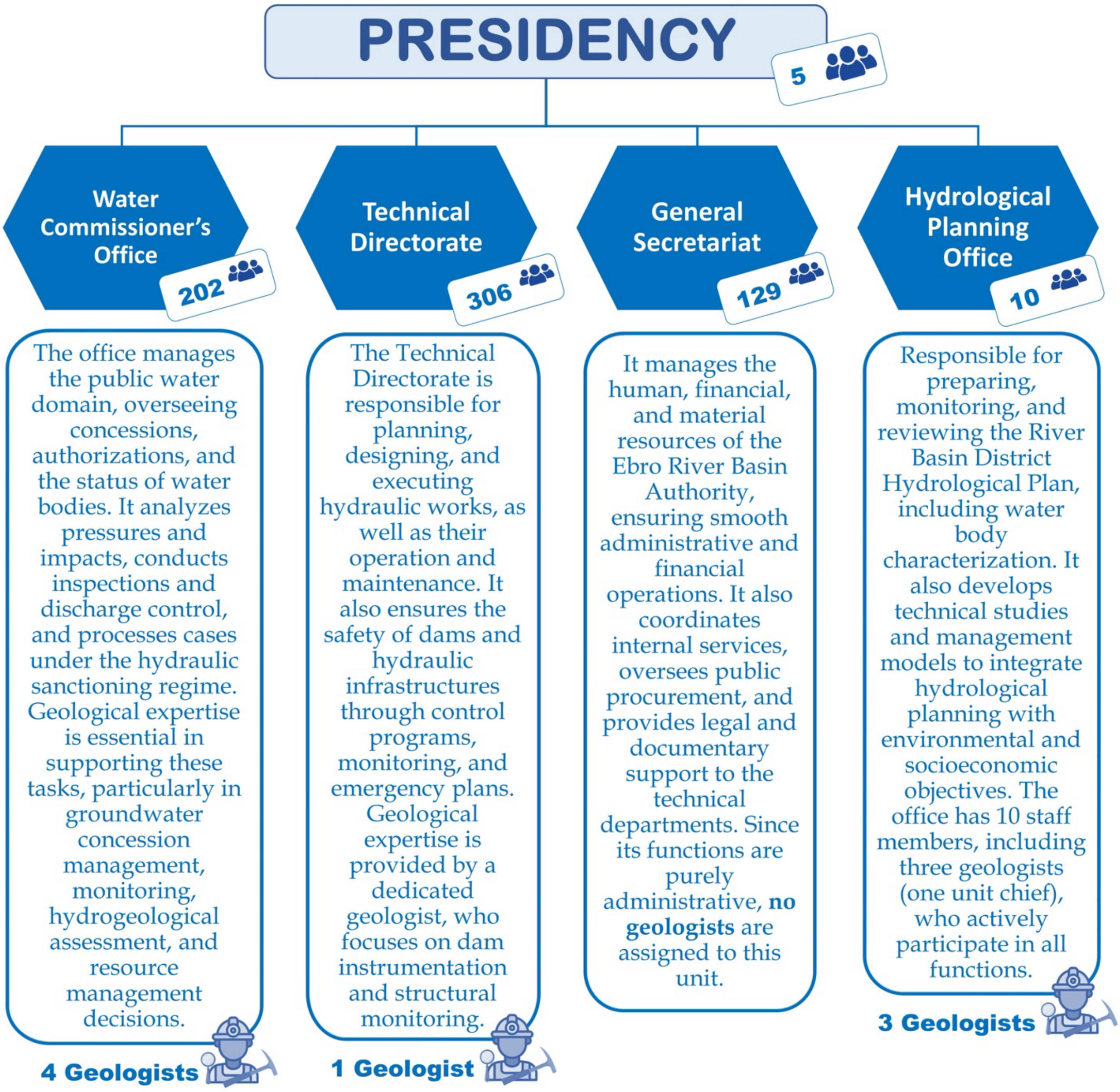


**Figure 2:** Administrative units comprising the CHE, including the Water Commissioner's Office, Technical Directorate, General Secretariat, and Hydrological Planning Office.

A key milestone in the administrative history of the CHE was the establishment of the Water Commissioner's Offices in 1959 [13], which professionalized functions such as discharge control, hydraulic policing, and the inspection of water uses. These tasks were organized into technical sections by the Ministerial Order of June 13, 1973 [14; 15; 16]. The 1985 Water Act and Decree 984/1989, which incorporated the Hydrological Planning Office, underpinned the current administrative configuration. Since then, the CHE has been responsible for continental water management, hydraulic works, and planification, including the integration of the Imperial Canal of Aragón [12]. This article focuses on the role of geology within three of these key units: the Technical Directorate, the Water Commissioner's Office, and the Hydrological Planning Office.

## 3. Geology in the Technical Directorate

The Technical Directorate of the CHE plays a strategic role in planning, executing, and supervising hydraulic infrastructures, covering both projects carried out by the CHE and those promoted by third parties. Its core functions include project design, construction management, reservoir operation, and technical safety oversight, integrating geotechnical studies and structural monitoring throughout the entire infrastructure life cycle. In addition, it is involved in environmental management, the implementation of European funds, and the digitalization of technical supervision workflows [17].

### 3.1. Historical Background

Manuel Lorenzo Pardo, the first Technical Director of the CHE, emphasized the value of geology and geography as essential foundations for hydraulic engineering, promoting a rational and science-based approach oriented toward agricultural and national development. His territorial perspective transformed hydraulics into a strategic discipline [18].

His first major project, the Ebro Reservoir (1916), introduced the concept of multiannual water storage or interannual regulation [19]. Its construction (1921–1945) led to the flooding of the La Rasa de Campoo floodplain. Initially, the Ebro Reservoir was planned as a small dam known as the Virga Reservoir. After an in-depth study of the valley's characteristics, it was proposed to significantly expand its storage capacity to 541 $hm^3$. The location was chosen based on favorable geological conditions, including competent sedimentary materials and a valley morphology suitable for a 26 m-high and 200 m-long arch dam [20].

However, the foundation on highly compressible glaciofluvial deposits led to differential settlements that caused the collapse of the Noguerol viaduct only months after its inauguration in 1952. This highlighted the need to reinforce certain concrete sections and strengthen the structure. Corrective measures included the implementation of deep foundations, the removal of unsuitable fills, the use of properly proportioned structural concrete, and metallic reinforcements, together with drainage systems and pore-pressure control [21; 22].

Today, the Ebro Reservoir plays a strategic role in ensuring water supply to one of Spain's most economically dynamic regions, the so-called Ebro Corridor. Furthermore, it sustains an ecosystem of significant ecological importance, characterized by high biodiversity in both plants and wildlife, and functions simultaneously as a nesting site and a migratory stopover for bird species [23].

Another example underscoring the importance of geological investigations in hydraulic engineering can be found in Clemente Sáenz's (1929) study, which examined the stratigraphy and hydrogeological conditions of the Las Torcas reservoir basin (Huerva River). The geological analysis enabled the rejection of the initial site, which had lower storage capacity, in favor of the 9 $hm^3$ reservoir. Furthermore, during construction, a Jurassic formation with potential leakage risk was identified and subsequently treated by cement injections to seal the faults [24].

### 3.2. Recent New Dam Projects (21st Century)

In recent decades, the CHE has undertaken a dozen major reservoir projects, including new constructions and dam heightening. In all cases, geology and geotechnical engineering have played a crucial role in addressing technical challenges appropriately, mitigating landslide and seismic hazards, and ensuring appropriate site selection.

An example of this is the Mularroya Reservoir, in Zaragoza. It was designed to store up to 103 $hm^3$ and to supply water to the Jalón Valley. The reservoir is fed via a 13 km transfer tunnel from the Jalón River to the Grío River. The reservoir basin rests on Triassic-Jurassic carbonate materials with high permeability, while the tunnel crosses fractured Paleozoic formations with potential induced seismicity that required careful assessment. This presented a significant geotechnical and hydrogeological challenge [25].

Among the measures implemented to address geological risks effectively are the use of a Tunnel Boring Machine (TBM) for the digging of the tunnel, instead of the drill and blast technique, the relocation of the spillway to better suit the geological conditions, the installation of impermeable cut-off walls, and the reinforcement of the tunnel lining. In addition, the 2015 Environmental Impact Statement (EIS) established environmental requirements and continuous monitoring [26; 27; 28].

The Yesa Reservoir is also a notable example. It is currently undergoing works to heighten the dam, which was constructed in 1959 and has a storage capacity of 447 $hm^3$. The heightening is under construction and is expected to increase the total storage capacity up to 1,079 $hm^3$. The reservoir rests on flysch and Eocene marl materials of the Pre-Pyrenees. Certain slopes have exhibited landslide activity, and induced seismicity has been thoroughly assessed.

To mitigate these risks, and following extensive investigations, drainage systems, anchors, cut-off walls, and comprehensive instrumentation (inclinometers, piezometers, etc.) have been implemented. All these measures ensure that the Yesa Reservoir will meet the required safety standards after its heightening.

Another example is the Itoiz Reservoir, in Navarra. This reservoir entered service in 2003 with a total storage capacity of 418 $hm^3$. The 122 m-high dam rests on calcareous flysch sloping toward the reservoir. In this case, the measures implemented included slurry injections, reinforcement of the abutments, and the installation of a monitoring network with accelerometers, piezometers, and seismographs. The monitoring budget exceeded €830,000, and additional measures were planned before the reservoir entered full operation [29; 30].

The CHE's extensive experience in dam construction, encompassing 55 large reservoirs, demonstrates significant practical expertise in ensuring proper execution across diverse geological settings. The examples presented here represent only a small subset.

### 3.3. Geotechnical and Hydraulic Monitoring

The CHE manages nearly fifty-five state-owned dams equipped with approximately 8,159 manual and automatic sensors, which generate around 3.5 million data values per year. These records include piezometric, thermal, deformation, stress, seepage, inclinometric, and temperature measurements. This volume of data is managed through the SAIH-GEISER system, which automatically alerts whenever critical thresholds are exceeded and enables the real-time activation of emergency plans. The system provides continuous monitoring of the main hydraulic infrastructures in the basin, ensuring rapid responses to structural or geotechnical anomalies [31; 32].

In the case of the Itoiz Reservoir, as previously mentioned, geotechnical monitoring has been crucial for detecting millimetric-scale movements on the left bank using inclinometers, piezometers, accelerometers, and extensometers, all connected to the GEISER system. These instruments enabled the correlating of piezometric variations with induced seismic activity after filling, which prompted specific corrective measures, including slurry injections, abutment reinforcements, and expanded drainage systems, to maintain the safety factor within the regulatory criteria of Royal Decree 264/2021 [33; 34].

## 4. Water Commissioner’s Office: Technical and Operational Roles

For geological and hydrogeological studies, the CHE’s Water Commissioner’s Office usually collaborates with external entities, such as the IGME, specialized hydrogeology companies, and TRAGSA (Empresa de Transformación Agraria, S.A.), a Spanish public company integrated into the state-owned holding company Sociedad Estatal de Participaciones Industriales (SEPI).

Key tasks performed by this unit include drilling boreholes, collecting samples, and monitoring both quantitative and qualitative groundwater control networks.

The unit also installs piezometers to model flow and heat transport in urban aquifers, such as the alluvial aquifer in Zaragoza.

Sediment dynamics in reservoirs, such as Ribarroja Reservoir, are analyzed through bathymetries and numerical models.

Additionally, the unit delineates protection perimeters for drinking water and irrigation intakes, and conducts geological and hydrogeological studies throughout the basin.

Key tasks performed by this unit include drillling boreholes, sampling, and monitoring for quantitative and qualitative [35; 36].

However, geological work carried out within the CHE is not limited to isolated or ad hoc scientific and technical studies; rather, it is structurally integrated into the routine activities of the Water Commission. The following are some representative examples of this integration.

### 4.1. Groundwater Concessions: Management and Technical Oversight

In the Ebro River Basin District, groundwater demand is estimated at approximately 466 $hm^3$/ year, accounting for about 5.5% of the basin’s total water demand (Figure 3). This figure underscores that groundwater use, in volumetric terms, is significantly lower than that of surface water [37]. However, groundwater plays a strategic role in securing potable water supply for numerous small settlements in sparsely populated areas of the basin, in addition to supporting other uses.

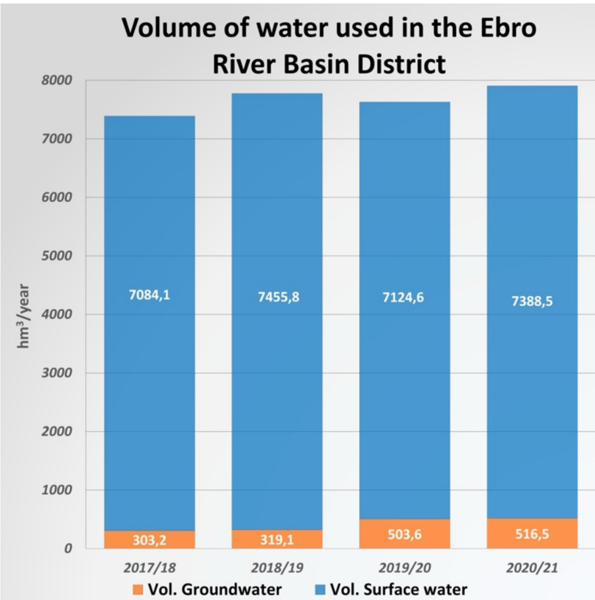


**Figure 3:** Comparison of surface water and groundwater use in the Ebro River Basin District (2017 to 2021).

All private water abstractions in the Ebro River Basin District must be supported by a formal water right, registered in the CHE Water Register or, in specific cases defined by the TRLA, in the Catalogue of Private Waters. New abstractions require a concession or administrative authorization, while certain legally established uses remain subject only to prior notification. These processes demand the expertise of technical teams within the Water Commissioner's Office, who oversee complex administrative procedures. Although groundwater accounts for only 5.5% of the total water volume, it represents approximately 90% of all registered abstractions.

The high number of groundwater abstractions imposes a substantially greater administrative workload compared to surface waters, both in terms of concessions initiated and resolved and the total number of processed files. Analysis of the 2015–2023 period confirms this persistent trend, underscoring that groundwater management constitutes a significant share of the Water Commissioner's Office's activities [38]. To facilitate these procedures, a dedicated team of hydrogeologists ensures the proper handling of groundwater users' applications across the basin. Moreover, certain abstractions require the submission of tailored hydrogeological studies or numerical models evaluating potential impacts on other abstractions, springs, or geothermal resources, which are subsequently validated by the Commissioner's hydrogeologists.

### 4.2. Groundwater Control and Monitoring Networks

The Ebro River Basin Authority (CHE) operates a consolidated groundwater monitoring network, established in the 1980s and later adapted to comply with the Water Framework Directive (WFD 2000/60/EC) [8]. The network integrates surveillance systems designed to safeguard, assess, and promote the sustainable management of the aquifers across the Ebro River Basin District.

Chemical monitoring is conducted to provide an overall assessment of the status of groundwater bodies and to detect significant trends in anthropogenic contaminants. In the Ebro River Basin District, groundwater quality is monitored through several integrated control networks comprising a total of 1,355 points (Figure 4). Many of these monitoring stations provide data for multiple networks. The following control networks are distinguished for tracking qualitative status:

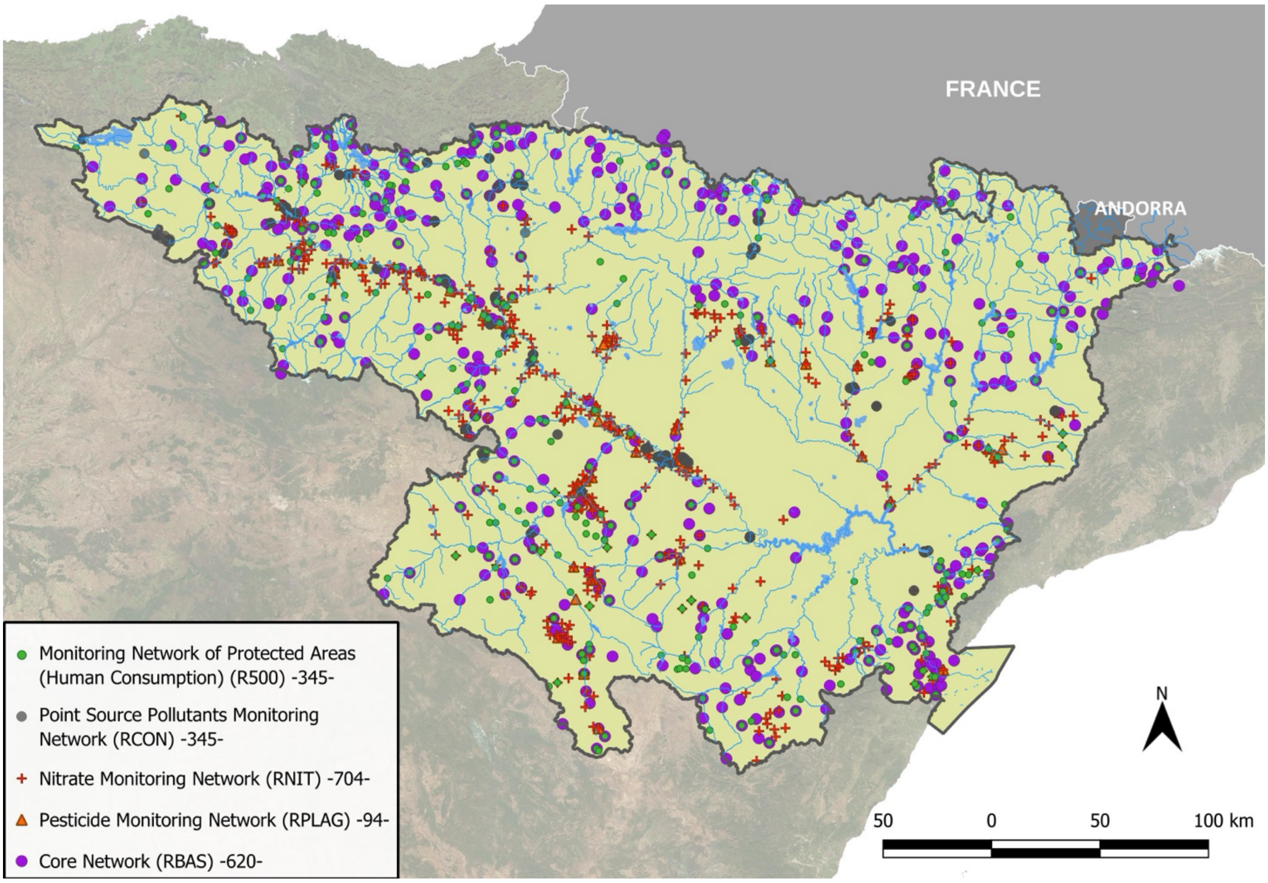


**Figure 4:** Locations included in the various groundwater quality control networks.

- The Surveillance Monitoring Program, as defined by the WFD and commonly referred to as the Basic Network (RBAS), performs semiannual sampling. The network comprises 620 stations where in situ measurements are taken for key parameters, including pH, conductivity, temperature, dissolved oxygen, and redox potential; major cations

(Na, K, Ca, Mg); anions (carbonates, bicarbonates, sulfates, chlorides); nitrogen compounds (nitrates, nitrites, ammonium); and additional indicators such as chemical oxygen demand (COD), phosphates, and silica.

- The Operational Monitoring Program, performing quarterly sampling, is organized into two control networks:
  - Nitrate Network (RNIT), comprising 704 stations.
  - Pesticide Network (RPLAG), comprising 94 stations.
- The Protected Areas Monitoring Network (R500), comprising 345 stations, is dedicated to monitoring water intended for human consumption. Sampling frequency in this network varies according to the size of the population served, ranging from 4 to 12 times per year.
- The Point Source Contamination Control Network (RCON) represents a targeted program, comprising 345 monitoring points that correspond to approximately 60 cases of industrially sourced groundwater contamination.

In addition, monitoring the quantitative status of groundwater in the basin is carried out through a total of 381 control points, encompassing both piezometric measurements and spring discharge. The following control networks are distinguished for this purpose:

- The Piezometric Network for monitoring the quantitative status of groundwater consists of 327 points, including 20 multiple piezometers. Water level measurements are conducted at least once a month, while 267 piezometers are equipped with automatic monitoring systems operating at fifteen-minute or hourly intervals (Figure 5).

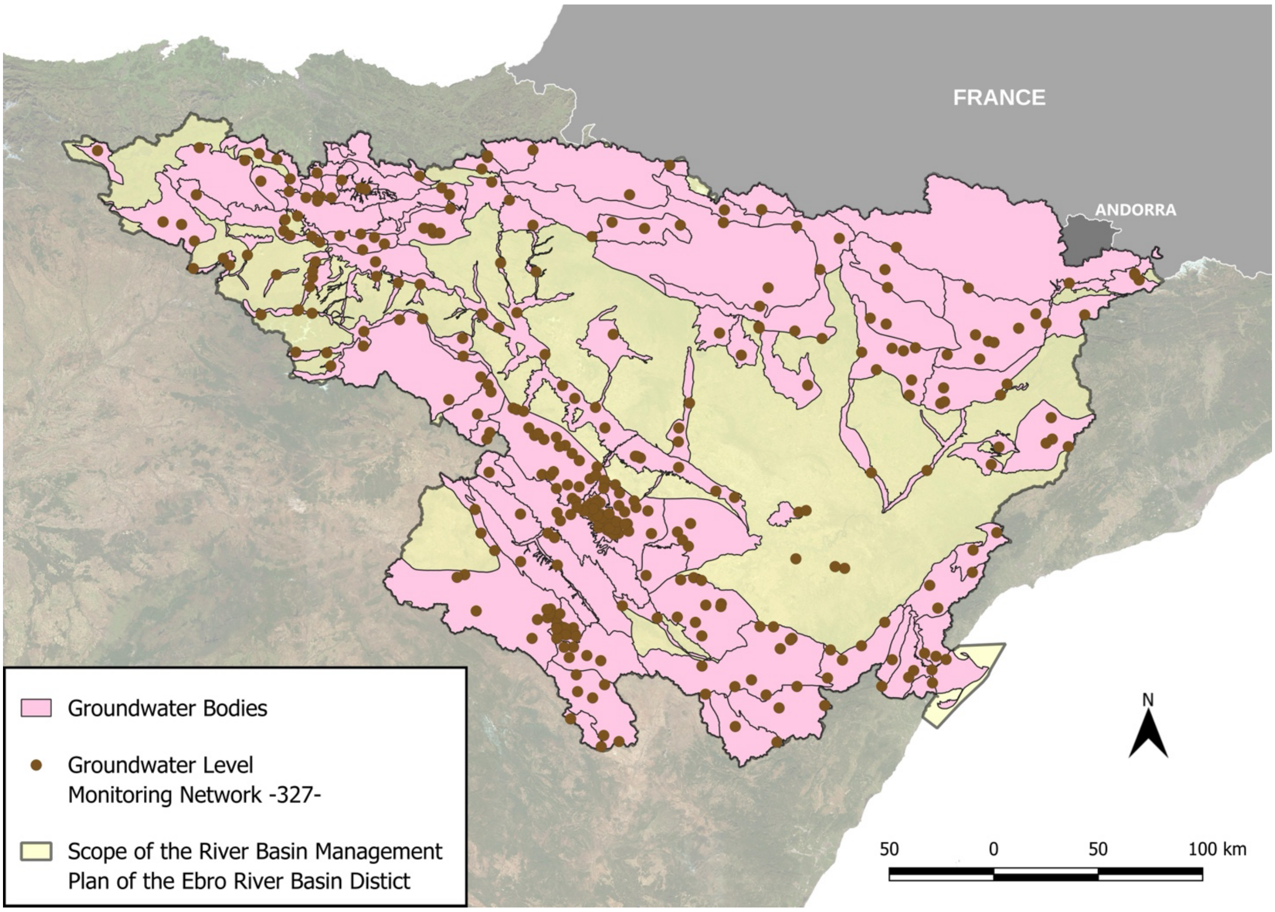


**Figure 5:** Monitoring points forming part of the piezometric network for quantitative groundwater assessment.

- The Foronometric Monitoring Network, comprising 54 stations, measures spring discharge across 101 gauging sections. Recent initiatives by MITECO indicate its forthcoming automation [39].

### 4.3. Groundwater Protection and Safeguarding

The Water Commissioner's Office has been pursuing multiple lines of action focused on groundwater protection. These include conducting targeted studies, developing relevant strategies, and managing procedures for aquifer decontamination.

Notable among these studies are the evaluations of the quantitative and chemical status of groundwater, along with contributions to characterizing areas impacted by nitrate contamination. Currently, MITECO designates these affected zones based on data from CHE's monitoring networks and with technical guidance provided by CHE staff.

A prominent example of strategic initiatives is the development by the CHE of the "Strategy for Combating Elevated Nitrate Levels in the Waters of the Basin" (NITRACHE Strategy) [40]. The strategy imposes stringent requirements on livestock waste management as a condition for obtaining water-use permits from CHE. As a consequence of this initiative, more effective management of livestock practices has been performed, promoting a more balanced distribution of pressures and consequently reducing nitrate concentrations in groundwater and surface water.

Since the mid-1990s, CHE has managed procedures requiring the decontamination of groundwater impacted by point sources, typically of industrial origin, primarily involving organic compounds (hydrocarbons, organochlorines, etc.) and metals. Although these contaminants usually affect limited portions of aquifers, they exhibit high persistence and toxicity. The technical complexity of these cases necessitates the presence of specialized groundwater experts within the administration, capable of interpreting, evaluating, and validating hydrogeological studies characterizing contamination, as well as the associated remediation projects and their subsequent monitoring. These tasks are undertaken by the Unit's team of dedicated hydrogeologists.

Another form of groundwater protection is the establishment of hydrological reserves, designated for water bodies of high ecological or geomorphological value, where specific restrictions are applied. These reserves are categorized into three types: fluvial—currently 25, totaling over 385 km of river courses; lacustrine—comprising 4 lakes; and groundwater reserves—with two groundwater bodies officially designated [41]. The identification of these water bodies has taken into account geomorphological and hydrogeological criteria, with active involvement from CHE geologists.

A further key initiative for groundwater protection in the Ebro Basin has been the establishment of protection perimeters for selected public water supplies. This initiative is still in its early stages, with two perimeters approved (Arteta Spring, serving Pamplona and San Julián de Banzo Spring, serving Huesca) and 19 technically delineated. Given the complexity of the approval and implementation process, additional efforts will be required in the coming years.

### 4.4. Permits for the Extraction of River Aggregates

At CHE, the management of aggregates has necessitated the expertise of geological professionals. Understanding fluvial dynamics is crucial for accurately characterizing the geometry of fluvial deposits, their natural behavior, spatial and temporal evolution, and for assessing the impacts and anticipating behaviors following extraction activities.

Aggregate extraction in the Ebro Basin is regulated by CHE through prior authorization, in compliance with the hydraulic public domain (DPH) regulations and its control zone (up to 100 m from the riverbed). Authorizations necessitate a technical project, verification of ownership, and, when applicable, an environmental assessment in accordance with Law 21/2013 [42].

These operations are subject to a fee determined by the value of the extraction and must be justified for hydrotechnical purposes (e.g., improved drainage or flood control), while also incorporating environmental restoration measures. Extractions with higher impact or located in sensitive areas require either standard or simplified environmental procedures. In all cases, the applicant must demonstrate, based on relevant geomorphological or hydrogeological studies, that the hydromorphological status of the water body in the affected reach will not be compromised and that the extraction is compatible with the conservation and upkeep of the hydraulic public domain and the maintenance of the water body in good condition.

Management is the responsibility of CHE's Water Commission, coordinated with regional administrations when environmental or mining competences are implicated. This requirement for collaboration has prompted institutional recommendations designed to harmonize authorization criteria [43].

### 4.5. Geomorphological Analysis – Flood Hazard Assessment.

CHE conducts geomorphological analyses of flood-prone areas as an integral component of flood risk assessment and management across the basin, incorporating the insights of geologists. These studies are embedded within the National Flood Zone Mapping System (SNCZI), developed in collaboration with MITECO and the autonomous communities, with the objective of identifying and classifying flood-prone areas according to various return periods (T10, T50, T100, T500), thereby supporting territory planning and risk management [44].

In this context, the Ebro River Basin Authority (CHE) provides a set of cartographic layers for geomorphological characterization. These include maps of alluvial deposits that help identify areas shaped by fluvial sediments and understand hydraulic dynamics, as well as datasets on endorheic basins, karst complexes influencing infiltration and flood propagation, and erosional features affecting riverbank stability and channel evolution. [45].

Furthermore, the Ebro River Basin Authority (CHE) collaborates in detailed studies for the development of flood hazard maps along specific reaches of the Ebro River, integrating geomorphological analyses that enhance the understanding of channel evolution and its interaction with the fluvial environment. These investigations support more effective risk management, consistent with initiatives such as Ebro Resilience, which foster territorial resilience to flood events [46]. To facilitate data accessibility and analysis, the CHE operates the SITEbro platform, which offers visualization and query tools for geospatial information related to fluvial dynamics and flood-prone zones across the Ebro River Basin.

## 5. Hydrological Planning Office

Geologists play a strategic role in hydrological planning by providing essential knowledge on the structure, composition and dynamics of the subsurface and river channels. Their geomorphological and hydrogeological analyses are fundamental to understanding infiltration processes, aquifer recharge, groundwater availability, bank stability and related hazards, thereby enabling the design of more effective and sustainable measures for water resource management and protection. The Hydrological Planning Office of the Ebro River Basin Authority (CHE) has promoted the following areas of activity particularly related to geology.

### 5.1. SitEbro

The Territorial Information System of the CHE (SitEbro) is the CHE's corporate geospatial platform. It serves both as an internal Intranet viewer for technical supervision, monitoring, and planning, and as a public Internet viewer, providing access to cartographic layers and hydro-environmental data of the Ebro Basin District, while promoting institutional transparency to society [47].

In terms of groundwater, SitEbro includes the specialized HydroGeoEbro viewer, which provides detailed information on groundwater bodies (GWBs) through hydrogeological layers covering hydrogeological–geological cross-sections, permeability, infiltration, vulnerability, piezometric surfaces, significant springs, river–aquifer interactions, and monitoring networks (piezometry and physico-chemical quality). In addition, it integrates the geological layers of the CHE and the IGME, in accordance with the Water Framework Directive [48].

SitEbro incorporates complete geological cartography through agreements with the IGME. This includes the GEODE maps (1:50,000), MAGNA, the national geomorphological map, and a specific coverage of alluvial deposits. This geospatial information underpins hazard analyses, morphodynamic evolution studies, and flood risk assessments [45].

The CHE geology layer, derived from the digitization of IGME cartography (2011), enabled the creation of basin-scale geological coverage, which was subsequently zoned into hydrogeological domains and units based on lithological and structural criteria. This information is incorporated into 1:200,000-scale maps as well as 1:500,000 (1995) and 1:600,000 (2019) synthesis maps, encompassing aquifer units, geological structures, and materials with hydrogeological potential [49; 50; 51; 52].

In summary, SitEbro enables integrated visualization of piezometric data, water quality, and vulnerable areas, facilitating overlay with geological and hydrogeological layers, thereby enhancing the technical planning and management of groundwater resources.

### 5.2. IPA (Inventory of Water Points)

The Hydrological Planning Office of the CHE manages the Inventory of Water Points (IPA), a database containing information on over 36,000 points mainly associated with groundwater. The database includes internal records, IGME data, scientific publications, and external technical studies, and is thus constantly updated [53]. It is accessible via the SitEbro geoportal, within the HydroGeoEbro module, supporting GIS-based download and access.

The IPA provides georeferenced, detailed information for each point, including construction characteristics, piezometric levels, operational conditions, and, when applicable, physicochemical parameters. It also serves as a central repository of all groundwater monitoring networks in the basin. Since 2009, real-time monitoring data have been incorporated for some points within the piezometric network [54; 55]. Additionally, the database includes quarterly piezometric measurements since the establishment of the network under IGME management, along with more recent data comprising daily averages from automated points and monthly measurements from manual points.

The IPA is integrated with the administrative management system INTEGRA, allowing the joint registration of water abstractions from the cases processed by the Water Commissioner's Office, thereby expanding the hydrogeological information and knowledge of the basin. This interoperability enhances data traceability and strengthens coordination between the Water Commissioner's Office and the Hydrological Planning Office, facilitating a more efficient and transparent management of the public hydraulic domain.

Projects focused on the "Redesign, Migration, and Maintenance of the Water Points Inventory (IPA) Application of the Ebro Hydrographic Confederation" will soon be undertaken to update it to current technologies and enhance its functionality.

### 5.3. Studies for Hydrological Planning

Hydrological planning in the Ebro Basin is grounded in technical-scientific studies conducted by the CHE, with the support of multiple collaborating entities. These studies have enabled the development of methodologies for the identification, delimitation, and characterization of groundwater bodies, as well as for the assessment of resources, pressures, and quantitative and chemical status. The information generated is compiled in technical datasheets, specific studies, and hydrogeological models, providing the foundation to define management and planning measures tailored to each hydrological cycle. The following highlights some of the main lines of work.

#### 5.3.1. Delimitation and characterization of groundwater bodies as recorded in the cycle-by-cycle plan

The definition and characterization of groundwater bodies in the Ebro Basin are conducted on a continuous, cycle-by-cycle basis, following the guidelines of the WFD [8] and the applicable national regulations [7]. This process is based on the integration of geological, hydrogeological, and hydrochemical data, as well as the analysis of pressures, resource uses, and the quantitative and chemical status of the bodies. The characterization enables the identification of vulnerable zones and the prioritization of protection and remediation measures, thereby optimizing Hydrological Planning [56].

The new hydrogeological characterization distinguishes two horizons: an upper horizon, comprising 32 alluvial or Quaternary groundwater bodies, and a lower or general horizon, encompassing 79 deep bodies of Tertiary and Mesozoic aquifers, which cover the entire basin. This segmentation ensures that all abstractions are incorporated within defined groundwater bodies, enhancing resource management, the Register of Protected Areas for human consumption, and the identification of vulnerable zones [57].

In the current planning cycle (2021–2027), 105 groundwater bodies have been identified, predominantly in the upper horizon, with the exception of two (Alfamén Miocene and La Galera Mesozoic), which belong to the lower horizon. For the fourth cycle (2028–2033), the CHE is conducting a review and redefinition of these bodies, while assessing their status and delineating protection perimeters to enable improved management of abstractions [57].

#### 5.3.2. Characterization Sheets of Groundwater Bodies.

The characterization of groundwater bodies in the Ebro Basin District is structured at two levels: an initial characterization and an additional characterization, incorporated in subsequent cycles as new information becomes available. The initial characterization sheets are produced for all groundwater bodies and include essential data on lithology, extent, hydrogeological typology, pressures, and impacts, forming the basis for assessing the status of each body [58].

The additional characterization sheets are prepared for groundwater bodies at risk and provide updated information on their delimitation, exploitation regime, predominant uses, and interactions with surface water bodies or dependent ecosystems. These supplements enable refining the assessment of chemical and quantitative status and more precisely guiding the Hydrological Plan measures to achieve environmental objectives [58]. Both types of sheets are available in the official Plan documents and are periodically updated as part of ongoing monitoring and review processes.

#### 5.3.3. Studies Related to Groundwater Resources

For the current Planning cycle, groundwater resources have been estimated using a comparative methodology, focused on assessing effective deep recharge. Compared with the SIMPA model from MITECO, which estimates a total infiltration of 7,931 hm³/year for the 1980/81–2017/18 period, the SCS-USDA curve number method was chosen, providing more conservative values (2,679 hm³/year for 1980/81–2005/06) by considering only the fraction of infiltration that reaches the saturated zone. Adjusting this series with factors derived from the SIMPA model, deep recharge has been updated to 2,824.2 hm³/year for 1940/41–2017/18 and 2,745.1 hm³/year for 1980/81–2017/18 [60].

Additional components of the water balance have been incorporated into this deep recharge, such as river infiltration and lateral transfers between adjacent groundwater bodies, derived from previous hydrogeological studies [61], allowing the resource to be defined under natural conditions. The available resource is calculated by subtracting an environmental reserve, set at 20% of the natural resource, validated through simulations with the PATRICAL model, considering the interannual variability of flows in dry years (mean-dry ratio of 0.75). Consequently, the available natural resource of the groundwater bodies amounts to 2,739.5 hm³/year [9], representing 17.5% of the total estimated natural regime for the entire basin.

### 5.4. Establishment of Constraints for Sustainable Groundwater Management

Based on previous work, the hydrological plan regulations establish management rules to ensure sustainable groundwater use. These rules essentially include restrictions on groundwater abstractions in certain areas of the basin, the requirement for internal regulation reservoirs to maintain ecological flows in associated rivers, minimum distances between abstractions in more intensively used zones, and limitations on the installation of farms near rivers in vulnerable areas.

These rules are necessary to ensure responsible water management. Their establishment relies on all available information, including geological and hydrogeological data (aquifer characteristics, degree of exploitation, piezometric trends, water contamination, dependent ecosystems, compliance with ecological flows, …). This knowledge is integrated and analyzed in the plans through a rigorous and participatory technical process. Undoubtedly, this is one of the most important phases in groundwater management. Sanjuan et al. (2025) [62] provides a more detailed discussion of this line of work.

These trends are closely linked to the hydrogeological characteristics and recharge capacity of the aquifer systems that dominate different sectors of the basin.

## 6. Mathematical Modeling of Aquifers

Hydrogeological modeling constitutes a key tool for the efficient management of groundwater, enabling the assessment of exploitation scenarios and management actions based on robust technical foundations. These models have been developed collaboratively among different units of the CHE, particularly the Water Commissioner's Office and the Hydrological Planning Office. External organizations have also provided decisive support for the technical development of these studies. Below, some examples of models implemented in the Ebro Basin are presented.

**6.1. Gallocanta**

The Gallocanta lake, the largest saline lake in Western Europe, is a unique ecosystem protected as an SCI, SCA, and Nature Reserve. Since 1988, the CHE has conducted water balance studies, including a hydrological model developed in the 2000s. Inputs from precipitation and runoff, as well as losses by evaporation, were evaluated for the period 1974–2001 [63].

Using the BALAN_11 model, infiltration inputs and lateral flows from nearby streams were estimated, with the analysis divided into six sub-basins [64]. Numerical modeling with Visual MODFLOW, structured into nine stratigraphic units, was calibrated using piezometric and streamflow data. The results indicated that, in the absence of pumping, the water table would not have been substantially affected during dry periods, although pumping was found to reduce stored volume in wet periods, without a direct correlation with the extracted volume [63].

All these studies were fundamental for establishing management strategies in the lake, aimed at optimizing groundwater withdrawals and implementing remediation measures against nitrate contamination.

**6.2. Modeling of the Miocene of Alfamén**

The Miocene Alfamén aquifer (groundwater body ES091MSBT077), located between the Jalón and Huerva rivers, were modeled under the leadership of the Water Commissioner's Office, with support from the Hydrological Planning Office. This area of the basin faces the most intensive groundwater use challenges.

It is a semi-confined unit of low to medium permeability, composed of sandstones, clays, and conglomerates, and is subject to intensive agricultural exploitation. Since the 2009 Ebro Hydrological Plan, this groundwater body has been classified as at risk due to overexploitation, with piezometric levels declining up to 40 m between 1988 and 2006, particularly in the Cariñena and Alfamén sectors [65].

The first numerical model was developed by IGME in 1983 [66]. Subsequently, CHE developed a detailed mathematical model. In 2013, an academic study supervised by CHE technicians (San Román, J., & Carceller, T.) described the system as consisting of three superimposed aquifers: 075 (Campo de Cariñena), 076 (Pliocene–Quaternary of Alfamén), and 077 (Miocene of Alfamén). Piezometric declines of up to 92 m were recorded between 1978 and 2013 in several piezometers, including P-13 (Cadillos) and Longares (2616-8-0106) [67]. In 2019, the hydrogeological characterization and modeling were updated, and the model is currently being further refined by the Complutense University of Madrid.

These studies have been, and will remain, fundamental for defining management measures in groundwater bodies under intensive exploitation. Notably, these measures include restrictions on water use in these aquifers, where no new extractions have been permitted for over two decades [68].

**6.3. Numerical modeling of the Oja River alluvial aquifer in La Rioja**

A detailed flow modeling example is provided by studies on groundwater body 45 (Oja River alluvial aquifer) in western La Rioja, led by the Hydrological Planning Office to evaluate this alluvial unit as a potential source for local water uses. The aquifer develops over Quaternary deposits associated with the Oja River and its tributaries and currently exhibits good quantitative status, although it faces risks of failing to hold a good chemical status due to anthropogenic pressures from diffuse agricultural pollution, mainly nitrates [65].

These studies have been conducted since the 1980s, addressing different phases such as the determination of the spatial distribution of hydrogeological parameters, piezometric, hydrometric, and water quality monitoring within the aquifer, identification of pollution sources, assessment of improvements in local water supply, and evaluation of the feasibility of maintaining environmental flows (year 2000), among many other aspects.

The first numerical modeling of the aquifer was developed in 2003 using the MODFLOW code. Subsequent studies concluded that, given the specific characteristics of this system, it was more suitable to design an ad hoc numerical tool to simulate, in a general way, groundwater flow and water balance in unconfined aquifers and their interaction with intermittent, low-flow rivers. Consequently, a specific study was commissioned from the University of Zaragoza, which implemented the finite volume method over a regular structured grid representing a fictitious aquifer domain. The resulting simulations provided piezometric levels at the grid nodes for a sequence of time steps. The system's hydraulic conductivity is relatively high (50–150 m/day), producing rapid responses to recharge events. The simulation was run with 6-hour time steps, covering the period from January 1, 1955, to December 31, 2001. Sensitivity analyses were performed for hydraulic conductivity (K), storage coefficient (S), and vertical permeability, adopting optimal values of K = 150 m/d, S = 0.05, and kver = 2 m/d. It was concluded that a rigorous parameter estimation required the application of an inverse modeling approach. Furthermore, a more realistic representation could be achieved through a more complex conceptual model in which the alluvial deposit was not considered uniform or isotropic [69].

All these studies proved highly valuable for analyzing alternative options concerning public water supply and the potential development of irrigation within the Oja River alluvial plain.

### 6.4. Modeling of geothermal installations in the city of Zaragoza

The growing use of low-enthalpy geothermal installations in Zaragoza, currently totaling 88 facilities, has prompted studies aimed at understanding their impact on the thermal regime of groundwater. Within the framework of an agreement between the IGME and the CHE [70], a coupled numerical model of groundwater flow and heat transport was developed from 2009 to 2013, focusing on the right bank of the Ebro River, where the majority of these installations are located [71; 72].

The finite element code TRANSIN IV was employed to integrate hydraulic and thermal data, calibrated with eight piezometers equipped with high-resolution pressure and temperature sensors. The model included 27 open-system geothermal installations, revealing that 26 % of the urban aquifer exhibits temperatures exceeding 18 °C, indicating sustained warming linked to the concentration of wells.

The study included detailed modeling of the 17.7 °C isotherm evolution under different temporal scenarios, as well as the thermal interference among three prominent installations located southwest of Zaragoza. Thermal self-interference was detected from the outset in some wells (Hospital Clínico), and an increasing effect was observed from the third year in certain locations (Complejo Aragonia), although uncertainties remained, due to limitations in the geological model of the area.

The analysis further emphasized that floods of the Ebro River and the dynamics of its banks play a key role in thermal redistribution, transporting energy several orders of magnitude greater than that generated by the geothermal facilities. The study concluded that the availability of accurate and detailed data on flows, intake and injection temperatures, and piezometric levels is essential for proper model calibration and validation.

Finally, the reversible operation of geothermal systems was recommended to optimize the thermal balance and minimize their impact on the aquifer. The study also highlighted the importance of considering the thermal behavior of the unsaturated zone, which exhibits progressive warming towards the surface.

These results and the currently available model, developed in FEFLOW, are employed to assess potential interactions between extractions during their administrative processing. In this context, specific analyses of interferences between certain extractions are maintained within the framework of an agreement between the Ministry and the IGME.

## 7. Future perspectives

Of the total 652 staff at the CHE [73], 8 are geology professionals. The tasks carried out over recent years highlight the essential role of this discipline in achieving rational and sustainable management of water resources. Looking forward, it is essential to continue implementing geological methodologies in water management, which is increasingly multidisciplinary.

In this regard, the Groundwater Action Plan 2023–2030 promoted by MITECO [74] underscores the efforts to improve the knowledge, management, and governance of groundwater in Spain. The Plan has a budget of nearly €26 million, of which €1.9 million are allocated to the CHE.

The first line of action underscores hydrogeological knowledge through the systematization of information in a new digital document manager (ADEPAS), homogeneous nationwide studies of groundwater bodies, and the development of numerical models. In the Ebro Basin District, new models are planned for 10 groundwater bodies at risk, while 10 existing models will be updated, giving priority to those subject to higher pressures, usage conflicts, or difficulties in attaining good status. User involvement will play a key role in data validation and scenario interpretation.

The second line aims to consolidate and enhance the monitoring networks, increasing the automation and representativeness of piezometers and chemical control points to ensure data reliability and adherence to recent regulations. This includes the integration of advanced technologies and technical training to manage risks related to nitrate contamination, saline intrusion, and overexploitation.

The third line focuses on safeguarding against contamination and overexploitation, by promoting the establishment of protection perimeters for water resources and associated ecosystems. Its implementation requires an updated guide to standardize methodologies for defining protection perimeters, which is currently being developed. This line also includes the promotion of underground natural reserves as a protective measure.

The fourth line, in line with the PERTE initiative for Water Cycle Digitalization, drives the digitalization of water usage in supply, sanitation, and irrigation. Its objective is to optimize consumption, enhance management, and reduce the use of fertilizers and pesticides. The ADEPAS application serves as the central platform for hydrogeological information to support these efforts.

Finally, the fifth line is focused on governance and the regulatory framework, covering the definition of objectives, mobilization of resources, regulatory development, policy implementation and evaluation, as well as conflict resolution.

This involves regulatory amendments, the establishment of Users' Communities (CUAS), and specialized training programs.

These work prospects point to a promising future for the integration of geology in water management.

## 8. Conclusions

The century-long experience of the Ebro River Basin Authority demonstrates that effective basin management requires a strong integration of geological and hydrogeological knowledge.

Since its establishment in 1926, the CHE has relied on geology as an essential component in the integrated management of water resources across the Basin District. Geology provides detailed knowledge of the physical environment and decisively supports efficient water resource management, highlighting the need for specialized personnel with geological and hydrogeological expertise.

In the context of hydraulic engineering, geological and geotechnical studies are essential for the design, construction, and monitoring of dams, canals, and other hydraulic infrastructures. They provide critical information for assessing structural stability and the dynamic behavior of materials, which is indispensable to ensure infrastructure safety, longevity, and the early detection of potential geotechnical risks.

In the field of groundwater management, geology plays a key role in accurately characterizing groundwater bodies, defining the structure and properties of the aquifers that compose them, and assessing their vulnerability to both anthropogenic and natural pressures. This knowledge supports the subdivision of the basin, which is essential for effective administrative and management planning.

Monitoring and control programs actively incorporate geological criteria in their design and in the interpretation of observed piezometric and chemical trends, facilitating trend analysis and ensuring compliance with the threshold values established under current legislation.

Hydrological planning cannot be conceived without a thorough geological understanding of the territory. To this end, it is essential to have robust Geographic Information Systems (GIS) that capture the main geological characteristics—such as lithologies, representative geological profiles, permeability and porosity maps, monitoring networks, maps of piezometric levels and water quality, groundwater abstractions, and restricted or regulated areas. It is also important to maintain a comprehensive Groundwater Point Inventory that provides access to all this information. Finally, extensive analytical and data integration studies are essential to synthesize the information required for sound decision-making processes that underpin the development of hydrological plans.

Finally, it is essential to emphasize the importance of developing numerical groundwater models that enable the simulation of different management scenarios. These models support informed and scientifically sound decision-making and ultimately contribute to promoting sustainability and achieving good groundwater status.

The Ebro River Basin Authority (CHE) applies a rigorous and multidisciplinary geological approach that contributes to optimizing the technical and administrative management of water resources. Given the need to integrate geological criteria into an orderly and integrated water management framework, it is essential to continue updating and systematizing geological data, strengthening institutional coordination, and promoting transparency of information, thereby ensuring adaptive, science-based, and sustainable management of the water cycle.

The experience of the Ebro River Basin Authority demonstrates that basin management without strong geological input is structurally incomplete. Long-term geological knowledge of aquifers, recharge processes, and subsurface structures provides essential resilience for water management under increasing climate variability and growing anthropogenic pressures.

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