Managing groundwater resources using a national reference database: the French ADES concept

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Research Article

Managing groundwater resources using a national reference database: the French ADES concept

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Abstract

Groundwater is an integral part of the water cycle and an essential human resource. Humans must protect this ever-changing heritage and preserve it in a sustainable way by understanding the physical and chemical properties of aquifers and monitoring their quantity and quality. Numerous studies have collected immense volumes of data that are difficult to access and not always comparable or of adequate quality. A pioneering national-scale database, ADES, was created in 1999 to store and make available quality data on French groundwater. This tool is freely accessible for/to water managers, scientists and the public. The data management system used in the database satisfies two important objectives: it is interoperable and based on a recognised groundwater reference system and provides high quality data to a large public. Data from different producers require normalisation and standardisation of system requirements to allow data integration and exchange. The database designers set up shared data models, and based the system on communal repositories of water points and hydrogeological entities. Nearly 102 million groundwater quality records and over 17 million water-level records are currently available, describing almost 61,800 stations. ADES makes it possible to visualise in "real-time" water level data for approximately 1500 stations equipped with GPRS (General Packet Radio Service) technology. ADES also provides, on a public website and via web services, public quantitative and qualitative data. ADES is an essential tool for developing groundwater services based on the FAIR guiding principles: Findable, Accessible, Interoperable and Reusable data (Wilkinson et al. in SD 3:160018, 2016)

Article highlights

- A unique database for storing and disseminating reliable, comprehensive, and up-to-dategroundwater data to a large public.

- An interoperable system based on a common reference system to ensure data reliability.
- An interoperable system based on a common reference system to ensure data reliability.

Keywords Groundwater · Database · Management · Information system · France · Open data

1 Introduction

Numerous groundwater studies have generated large volumes of data that are difficult to access and reuse. The development of monitoring technology and information systems has made it necessary for all scientific disciplines to initiate data collection in central or interconnected databases, following strict rules that enable information sharing [1, 8, 9, 17, 19, 21, 36]. At the European level, the Water Framework Directive (WFD; [11]) established a structure for community action in the water policy field. The WFD imposed dense monitoring of all water types

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(groundwater, and surface- and coastal waters) for an accurate quantity and quality assessment. Implementation of the WFD also led to the development of water information systems. European countries thus had to improve or create national or regional databases to manage large volumes of data; they also had to share information among water actors in neighbouring countries, and with scientists in other foreign countries [20, 22, 30]. Unfortunately, not all the resulting databases are public and easily accessible, although some can be accessed through the internet. In Europe, the Open Data Directive [12] and more recently, the Proposal on European data governance (Data Governance Act [13]) have recognised the importance of data sharing.

Accurate and reliable ground- and surface-water information (including quantity and quality) is critical for planners and decision makers. Therefore, data collection, monitoring, storage, and availability in a management system is an integral part of any water resource strategy [24, 27, 32, 37]. Groundwater data should be based on internationally recognised geological and hydrogeological references such as those developed within the Groundwater Standards Working Group of the Open Geospatial Consortium (OGC) [9].

Various database models have been established to satisfy specific initial requirements. Some databases gather multiple types of information. In France, different specific databases have been established for each type of water and its associated information. This article is an overview of ADES (Portail national d'**A**ccès aux **D**onnées sur les **E**aux **S**outerraines), the French reference database for national groundwater resources and their management. The objective of this article is to show the importance of both strong quality assurances based on recognised national references and easy access to data for the general public. This article provides an overview of the ADES database, its implementation, the actors, the challenges encountered, the ways data are exchanged with models and repositories, database contents, and associated website and web services.

2 Materials—Water and environment versus the database concept

A review of the concepts and structure of various databases from around the world shows differences reflecting i) national priorities and strategies and ii) database content (type of support, parameters). Table 1 shows several databases, their country of origin, data contents, database links, and references to published articles. The databases are classified according to models based on the data they contain.

France has chosen a different approach, consisting of specific databases for each water type and its associated information, in addition to a common information exchange system. Several portals have been established for specific water and data types, such as "Naïades" for surface water quality (www.naiades.eaufrance.fr); "Hydro" for surface water level and flow rate (www.hydro.eaufrance.fr); "Quadrige" for coastal and marine water quality (https://quadrige.eaufrance.fr/), and "ADES" for groundwater quality and quantity (www.ades.eaufrance.fr).

The creation of the Hub'eau platform services (https://hubeau.eaufrance.fr/) in 2018 made the information from these databases accessible in a single site. These databases are all part of the Water Information System (SIE, www.eaufrance.fr), added to the Environmental Code by the French Water and Aquatic Environments law (law n°2006–1772, December 30, 2006). SIE was created to share and make available public sector water data. Hub'eau was thus designed to meet stakeholders' needs for public environmental information in the water sector.

3 Methods

3.1 The ADES national database concept

The need for a single site for storing and disseminating public French groundwater data led to development of the ADES database (www.ades.eaufrance.fr), initiated in 1999 and operational in 2002. The ADES system had to accommodate new data acquired for WFD monitoring, and also historical French data that complied with the national Open Data Policy. ADES is the result of a joint effort of the French geological survey (BRGM, which is in charge of development, maintenance, and operation of the ADES database), the Ministry in charge of Ecology, the Office of French Biodiversity (OFB), the Ministry of Health, the Water Agencies, and regional environment directorates (DREAL, Regional Directorate for the Environment, Planning and Housing).

The ADES system is based on monitoring networks for either groundwater quality or quantity that belong to a single producer. Each network is focused on one of three possible groundwater network objectives: general knowledge, use, or impact. The networks consist of measuring stations that provide data to producers. A station monitored for water quality may belong to several networks managed simultaneously by different partners. However, for quantity, only one producer can monitor an observation well for a given period, or different producers can follow each other over time. This management practice is related to the excessive complexity of managing the

Table 1 International database examples

Portal type	Country	Data	Link	References
Multi-target portals	Belgium	environment, health, education, sport, agriculture and population	https://data.gov.be	
	Australia	agriculture, climate, environment, and water (surface, coastal and ocean)	http://www.bom.gov.au	
	Quebec (Canada)	health, environment, energy, tourism, sport and education	https://www.donneesquebec.ca	
Multi-target environmental portals	Denmark	groundwater, drinking water, raw materials, environmental and geotechnical data	http://data.geus.dk/JupiterWWW/index.jsp	[18]
	Switzerland	geology, water, mineral resources, energy and geological hazards	https://www.geologieportal.ch	
Surface and groundwater portals	Portugal	surface and groundwater	https://snirh.apambiente.pt/	[6]
	United States	surface and groundwater	http://www.waterqualitydata.us	[29]
Surface, groundwater and coastal water quality portals	England	surface, coastal and groundwater	https://environment.data.gov.uk/water-quality/view/landing	
	Austria	surface, coastal and groundwater	https://wasser.umweltbundesamt.at/h2odb/	
All water type portal	Spain	all water type	https://www.miteco.gob.es/es/agua/temas/planificacion-hidrologica/sia-/infovisor.aspx	
Geothermal and Groundwater portal	New Zealand	geochemical, hydrological and geophysical information	https://ggw.gns.cri.nz/ggwdata	[23]
Groundwater portal	Canada (British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Québec, Nova-Scotia, Newfoundland and Labrador, Yukon)	groundwater	https://gin.gw-info.net/	

measurement references of various potential producers. Moreover, today, the trend toward equipping observation wells with continuous data acquisition units eliminates the need for several organisations to monitor the same well. This change also facilitates more efficient monitoring and decreases associated costs for data producers.

The ADES database currently contains several million records on groundwater quality and quantity, acquired from more than 245 individual networks covering more than 61,800 stations and monitored by over 180 organisations. In addition to these unitary networks, there are also 67 meta-networks, groups of unitary networks containing some or all of the points of the primary networks. These meta-networks serve to combine into the same network different points that have the same purpose, but are monitored by different producers. Current data producers are territorial or local authorities, public institutions, in addition to decentralised government services (water agencies, regional health agencies, departmental and regional councils, BRGM regional offices, etc.). The list of current data producers also includes some private unions and associations.

Information contained in ADES involves networks, measuring points, and the results of quantitative (water levels) and qualitative (physical and chemical parameters) measurements.

In setting up the ADES database, its designers encountered several challenges. The database had to be i) a tool for gathering and storing information on groundwater; ii) a communication tool and iii) a water management tool. Regarding communication, the tool should allow the availability of public groundwater data and their exchange on a single, free website. Water management needs included local water management and European WFD priorities, in particular implementing and

evaluating groundwater resources monitoring and water management plans.

The presence of all public groundwater data on a single website facilitates access to and treatment of groundwater issues in France, and provides multiple opportunities for study and research. Scientists with the expertise to interpret and integrate such data will be able to answer relevant questions on a national or regional scale, as Baran et al. [3] and Ebengue Atega et al. [10] did, for example.

3.2 Water data exchange models

Perkins et al. [28], as well as Read et al. [29] and references therein, highlight the need for standardised databases. Therefore, in order to aggregate and standardise data from different producers, data models shared by all have been set up. In France, the National Water Data Secretariat (Sandre; www.sandre.eaufrance.fr) develops a common water data language and repositories for the Water Information System. The SANDRE has established French *data models* for the exchange of groundwater quality and quantity data. Data models are structures for exchanging data and their metadata ("data on data"), essential for understanding and interpreting the data. Such data models are described in *exchange scenarios*, specification documents that describe how to exchange data in a specific context. These exchange scenarios are used for exchanging data by using a specific format. These documents provide details of the exchange: semantics, mandatory and optional information, syntax, the exchanged data, and technical and organisational modalities. *Data dictionaries* are specification documents that describe and clarify terminology and data for a particular field. These dictionaries describe aspects of the data, including their meaning, essential drafting or codification rules, the list of possible values, the persons or organisations who have the right to create, consult, modify, or delete them, etc. ADES database, from data integration procedures to their exposure, are based on these dictionaries and exchange scenarios.

To store data in ADES, data producers must inform the project management team, which then gives them specific rights on the monitoring network(s), the theme(s) (quality and/or quantity), as well as on the measurement station(s). In addition, data producers must respect a specific exchange model for each data type (quality or quantity). Consistency checks are carried out at the time of data integration to ensure that the data model is respected. Transmitted information that does not comply with the data model is refused, and the producer is informed. The producer must then correct the errors to re-submit the data. As mentioned above, the data model includes the metadata necessary for an accurate description of the data. For example, chemical data cannot be stored without

specifying the associated measurement unit. Most metadata are entered into mandatory fields and data cannot be stored without these fields. Indeed, as Sprague et al. [33] point out, metadata are essential for understanding and therefore using the data. In addition, metadata must be well-precise and unambiguous, as data become unusable without the transmission of information on the accompanying metadata, and the efforts deployed for data acquisition are then wasted.

For all quality data, i.e. for each chemical analysis, 40 fields, including the measurement itself, are requested, and 18 fields are mandatory for data submission, including measuring point, sampling date, data producer, parameter, unit, analytical method, and laboratory, etc. The producer also can complete information on the samples containing the different analyses, such as on sampling depth, flow rate, purged volume, sampling and preservation methods, etc. For groundwater levels the data model is simpler, consisting of eight mandatory fields (date, measuring method, etc.). Among the mandatory fields, the data producer must indicate the status and qualification for each data item. Data status refers to the progress of data validation, from raw data (from the acquisition process and not examined) to data verified at different stages (value seen by a human or automatic expert system). Qualification indicates whether the data verification, if it was done, is correct, uncertain, or incorrect. The producer can at any time change the status and qualification of the ADES data. For example, the producer can store raw data in the database and modify the status and qualification after the necessary consistency checks are done. Similarly, data producers can correct erroneous data or metadata (on data, measuring unit, date, etc.) at any time. In fact—since each data item is linked to the producer who entered it—if a value seems doubtful, the producer can be contacted at any time to verify the value or correct it if necessary.

3.3 The groundwater reference system

All metadata are coded according to a precise reference system shared by the different users of the French water information system, according to the specific focus of each system. The national Water Data Secretariat (Sandre) administers most shared repositories, such as parameters, measurement units, fractions analysed, support, analytical methods, etc. Other reference systems, specific to certain subjects, are developed by other organisations and only distributed by the Sandre. For groundwater, BRGM manages the reference system for French water points as well as the reference system for hydrogeological entities. Regional water agencies manage groundwater body references for the WFD.

Reference system management is now evolving towards systems recognised at the European and international levels, such as the OGC (Open Geospatial Consortium), which proposes a conceptual and logical model for groundwater data exchange called groundwaterML [8, 9]. Indeed, the use of common reference is an essential part of data quality assurance and an open access process allowing data reuse for environmental studies.

3.3.1 Hydrogeological entity references

Groundwater management responds to economic, societal, and environmental issues that require a suitable knowledge of the subsurface and its physical properties, to assess water status and to guide any actions to be taken for resource preservation. The hydrogeological reference database of aquifer boundaries (BDLISA; https://bdlisa.eaufrance.fr/) is a national tool that provides a scientific framework in the field of hydrogeology. BDLISA is a cartographic reference system of the Water Information System. This database has been defined and established at the 1:50,000 scale; thus all (hydro)geological objects in the French territory have been mapped and described at this scale. This division into hydrogeological entities is a finer division than that of water bodies, which are the reporting units for the European WFD (www.wiser.eu).

Most monitoring points are related to a hydrogeological entity, BDLISA, and a groundwater body, indicating the formation in which the measurements were made.

3.3.2 Water point reference

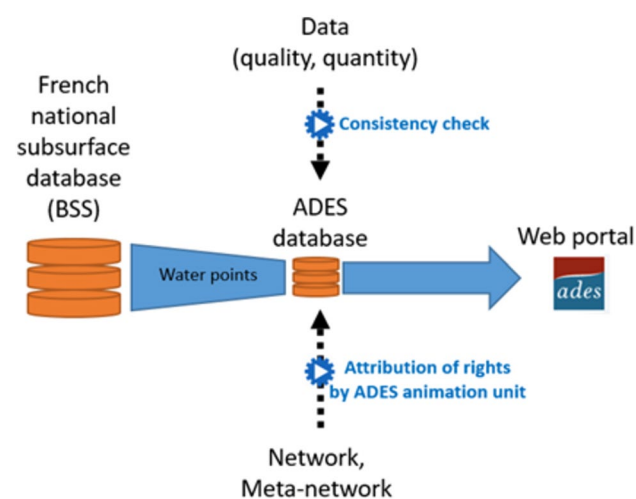Each measurement site is referenced in the repository of water points (Fig. 1), which is part of the French national subsurface database (BSS). The BSS is organised and is managed by the French geological survey (BRGM). The BSS contains information on underground structures (boreholes and wells) and work carried out in France for more than a century. Most of the data come from drillers, operators, and engineering and design departments, and are freely accessible via Infoterre (http://www.infoterre.fr/). Each site is identified by a unique national station code (BSSID). The BSS database contains 888,900 points of which more than 523,700, or about 60%, are water points.

The information stored in the subsurface database consists of four primary parameter types, all of which are linked to ADES (Fig. 1). They are: i) Location of the measurement point (department, city, coordinates, altitude, etc.); ii) Technical information about the point (depth, technical sections, and borehole equipment, etc.); iii) Geological information (cross sections, lithology, lithostratigraphy, chronostratigraphy); and iv) Hydrogeological information, such as the nature of the water point (borehole, spring, etc.), the reservoir type (free, confined, semi-confined, etc.), the status of the water point (operational, plugged, etc.), and the water body and the hydrogeological entity.

Groundwater points have been linked to groundwater bodies and the BDLISA reference system for several years. These links are fundamental for identifying the water body or hydrogeological entity to which the data refer. In particular, they make it possible to process data at the scale of water bodies, as required for WFD reporting. Understanding of the link between water points and aquifers has facilitated, for example, the work by Valdes et al. [34], who used chemical data from ADES to determine average geochemical properties in the Chalk aquifer of the Upper Normandy region in France. Of the more than 61,800 water points monitored in ADES, over 85% are assigned to a hydrogeological entity and nearly 97% to a water body.

Information related to water point monitoring is stored in ADES. This includes initial and final monitoring dates, the water level measurement reference (top of casing, ground level, etc.), the frequency of data acquisition, methods used, etc.

3.4 Content of the database and overview of the data set

3.4.1 Measurement points

ADES contains more than 61,800 water points with data. Among these, over 4,360 points are used for water level measurements, more than 58,600 are used for water quality—called "qualitometers" in ADES—and about 1170 points have both types of monitoring. These stations are located throughout metropolitan France (Fig. 2) as well as in the five French overseas departments (Reunion,
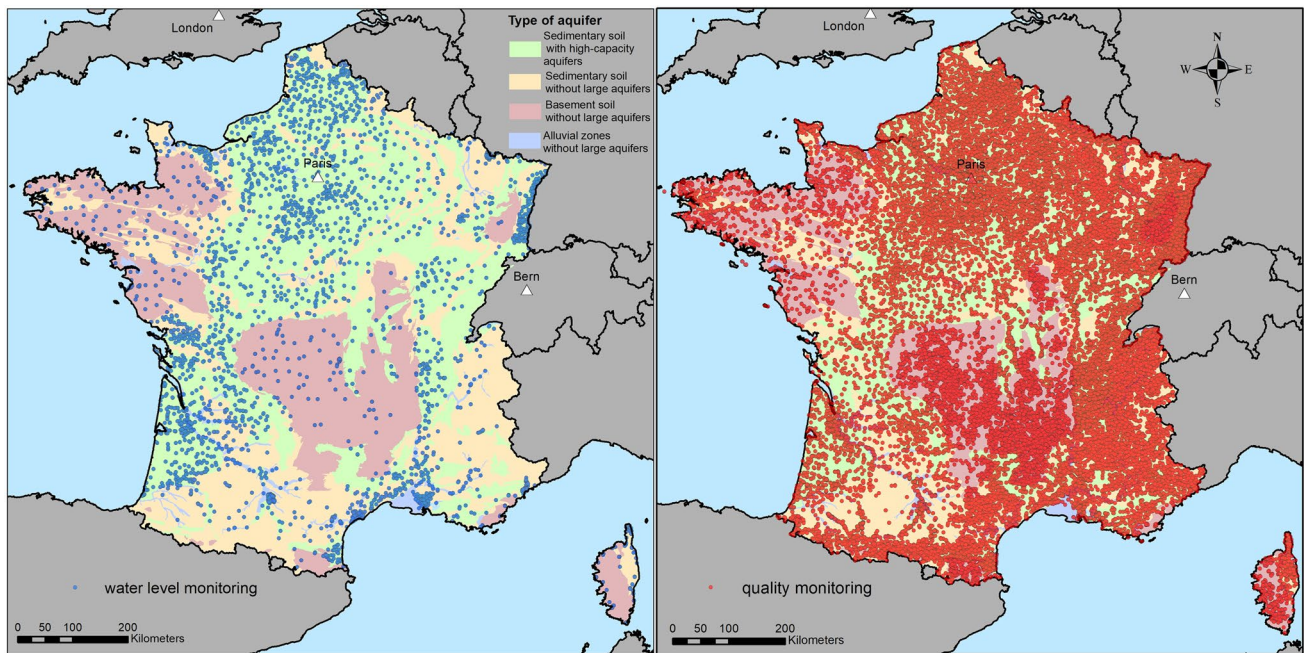

Fig. 1 Layout of the ADES concept and workflow

Fig. 2 Map of monitoring stations available in ADES, not including BRGM observation wells (wells outside monitoring networks)

Martinique, Guadeloupe, French Guiana, and Mayotte). In addition to these stations, BRGM holds data on 17,600 observation wells that it manages and that are not part of monitoring networks. In 2020, BRGM decided to make the data from these additional stations available via ADES.

The spatial distribution of the measuring stations of the ADES networks (Fig. 2)—and thus of the data—vary according to several factors, including local geology, the presence, type, and extent of aquifers, the existence of groundwater access points, groundwater use (mandatory monitoring for drinking water), the presence and monitoring of potential pollution sources, and the regulatory texts governing groundwater monitoring (national water laws, European WFD, etc.).

Monitored water bodies are primarily those that lie within sedimentary and alluvial environments; they are often large aquifers under high anthropogenic pressure. For example, in France's two largest sedimentary basins, Paris and Aquitaine, agriculture is highly developed, leading to pressure on groundwater resources. Furthermore, the development of cities and industry along rivers creates additional pressure on alluvial aquifers.

The number of new measuring stations added to ADES each year illustrates the various policies that have been successively implemented over time, as well as the development of specific networks. In terms of water quality monitoring, for example, the increase in the number of points between 1980 and 2020 (Fig. 3) shows that groundwater quality monitoring in France had been initiated well before implementation of the European WFD in 2000. Moreover, the large increase in the number of quality monitoring stations in 1996–1998 is related to the initiation of data transfer from groundwater quality monitoring networks for drinking water supply into ADES. Implementation of the WFD monitoring networks can be observed in 2003–2004. Since 2004, the number of new "qualitometers" has consistently declined, with an average of only about 400 new "qualitometers" per year over the past 10 years. The reason for this slowdown in the number of new installations is that France has now reached the coverage required by the WFD and that the cost of such monitoring is significant. New stations are either replacements, after abandoning a station that has become inaccessible, or new stations that are part of new monitoring networks, generally supported by watershed associations or communities of municipalities that want to make their data available.

3.4.2 Water level data

Quantitative data consist of a groundwater level, expressed as a measured depth, then translated into an elevation expressed in NGF (French height reference system). In the current system, only one datum per day can be stored per monitoring point. Generally, for points equipped with automatic acquisition systems, the measurement frequency is hourly. Therefore, only the maximum daily elevation value (expressed in NGF) is stored because
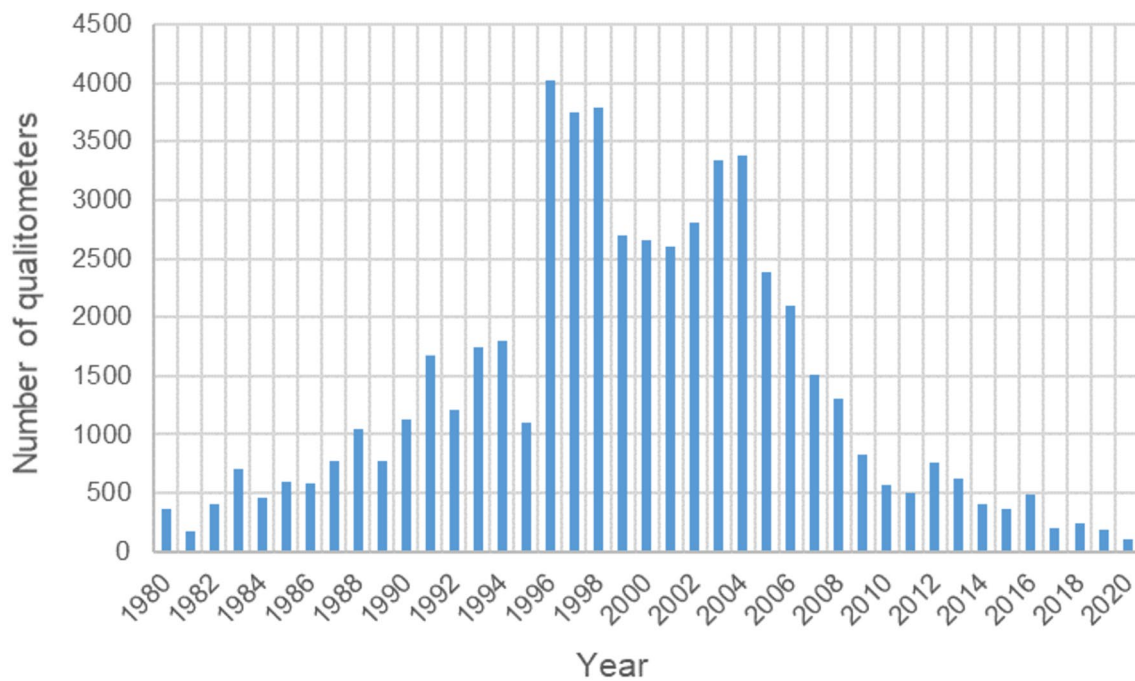
Fig. 3 Number of new "qualitometers" in ADES per year between 1980 and 2020

it represents the shallowest depth and therefore the value closest to the static water level. More than 17 million water level records from more than 4,360 stations were stored in ADES in January 2021. In recent years, an average of 1 million records were stored in ADES annually. About 2% of points have only one measurement. Such points were often part of transitory networks whose data were used for constructing water level maps. The observation well with the most data (more than 18,200 water level measurements) is located in southern France and has been monitored since 1970.

The observation well with the longest monitoring history is located in northern France, dating back to March 1899. Still active, it has nearly 11,200 records in ADES.

Moreover, as mentioned above, data from 17,600 BRGM observation wells were added to ADES in 2020. The number of measurements associated with these points exceeds 1.5 million. However, for 40% of these specific points, only a single measurement was available. Generally, such a measurement was made at the end of drilling, or was needed to construct a water level map. The oldest water level measurement dates back to 1829, when a 70-m-deep borehole was drilled north of Paris in Lutetian limestone.

An important number of today's water level monitoring stations are part of the Water Framework Directive network. BRGM manages more than 1,620 stations out of the 1,770 active stations in the network. This network also belongs to the OZCAR-RI, French Network of Critical Zone Observatories (www.ozcar-ri.org).

As technology evolved, it was possible to move from one-time measurements (usually monthly) to continuous data acquisition with recorders that required regular downloading. As a result, the increase of remote data transmission has eased data collection. Stations can now be remotely interrogated as often as desired, thus reducing field work needed for data collection. Instead of loading data into the ADES database, the current trend is to make "raw" data available in real-time, which has now become a necessity given society's current needs and expectations (water resource quantity and quality, etc.). The availability of real-time data from environmental sensors is a challenge for rapid data exploitation [38].

For the 1,500 stations equipped with GPRS technology, the previous day's raw hourly data are sent to the BRGM website each morning, for later display in ADES. Such raw data are broadcast in "near" real-time and have not been validated. Conventional data storage and validation processes take place in the next few days. The data made available in near real-time are, for example, taken up and used by the website Métééau Nappes (https://meteeaunappes.brgm.fr), a tool for real-time monitoring and forecasting of water table data.

3.4.3 Quality data

The ADES database contains nearly 102 million records of groundwater chemical analyses acquired at more than 58,600 different measuring points. Between 2015 and 2019, the average annual number of new quality analyses was approximately 10 million, ranging from 7 to 16 million. The average number of records per monitoring point exceeds 1,700. Only 0.6% of the points have only one record. The point with the most records is a spring located in southern France, which is part of the WFD quality monitoring network European reporting. More than 70,800 analyses were acquired between 1988 and today from more than 300 samplings events at this monitoring site. The amount of data has constantly increased over time. ADES contains 25,000 quality records for 1980. By ten years later, between 1992 and 1993, the number of records in ADES per year had increased by ten times (about 250,000 records). The number of records has grown steadily from year to year, reaching 2.6 million records per year in 2008. After 2008, the number of records continued to increase, reaching 93.3 million per year in 2018. The increased number of analyses is related to the increased number of qualitometers installed and the increased number of parameters analysed. The apparent decrease in the number of analyses for 2020 is related to a variable delay, depending on the producer, between taking the measurement and putting it into the database.

All data are freely available for public or scientific purposes, as demonstrated by Barbier [4] who used the ADES database to define the link between the water cycle and the chemical composition of groundwater in France. The water quality data consist of physical, environmental, microbiological, and chemical parameters, including additional parameters related to natural water mineralisation (major, minor and trace ions) and organic micropollutants (pesticides, pharmaceuticals, industrial pollutants, etc.). The list of parameters that ADES can accept comes from the national parameter repository administrated by the Sandre, which consists of 5,550 different parameters and is constantly evolving. As various SIE partners and water data producers request new parameters, they are added to the repository. ADES regularly incorporates all new groundwater parameters from the repository. ADES currently includes 3,880 different parameters related to groundwater. Data are available for approximately 2,770 different parameters, of which 60% have more than 1,000 individual record. Around 400 parameters appear in more than 10,000 analyses.

The ten most commonly measured parameters (between 778 000 and 434 000 records), ranked in descending order, are: hydrogen potential (pH), nitrate, ammonium, water temperature, nitrites, sulphates, chlorides, turbidity, iron, and conductivity. These physico-chemical and chemical parameters represent general groundwater characteristics. These classic parameters have been monitored in groundwater for many years. They account for nearly 5.5 million, or 5.6% of the records.

Data distribution by parameter class indicates that 83% of the analyses in ADES represent organic micropollutants, with over 83.8 million data. Chemical parameters of mainly natural origin represent 12% of the records (12.1 million records). Physical (water temperature, conductivity, etc.), environmental (odour, colour, etc.) and microbiological parameters represent 5% of the data set.

The ten most frequently researched organic micropollutants (between 320 000 and 271 000 records) are all pesticides. Ranked in descending order, they are: atrazine, simazine, atrazine desethyl, terbuthylazine, atrazine deisopropyl, diuron, isoproturon, chlortoluron, linuron, and metolachlor. Despite their recent appearance and thus shorter monitoring history, they represent over 2.8 million of ADES records, which makes it possible to conduct effective statistical data treatment [3].

4 Results and discussion

In addition to data collection and storage, a database should be able to share data with the public and exchange data with other databases [8, 15]. From its origin, ADES has been envisioned as an open-access database and recently it has evolved into a database that is accessible through tools that make it possible to combine groundwater data with environmental data sources and to be updated regularly.

4.1 Web interface and web data services

The ADES data distribution chain involves numerous technologies adapted to a broad range of users and applications (Fig. 4). The ADES database can be used at several stages of the data life cycle. This includes storage and management of data after its acquisition, the provision of data through a dedicated portal, and the use of various services (Application Programming Interfaces API, Web Map Service WMS, Web Feature Service WFS, web monitoring service, etc.). After integration into the BRGM data lake, ADES data follow several distribution vectors. Users can access the data by various means: the web interface, web services, or by APIs. The Hub'Eau portal disseminates APIs that are commonly used in portals or services that use data. Examples are the PIC'Eau portal, which disseminates statistical processing in the form of APIs, and the MétéEau Nappes portal, which offers visualisation and forecasting
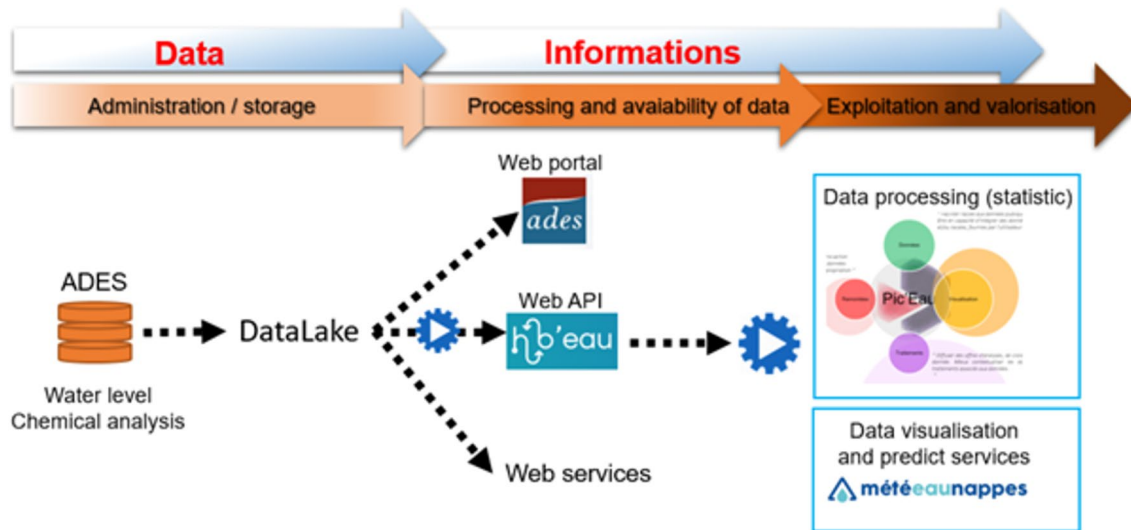
Fig. 4 Layout of the ADES data distribution chain

services for certain characteristic points, and for climatic and withdrawal scenarios.

4.2 The ADES web site

The user can use the web interface to search data by type (quality or quantity) using geographical criteria at various scales, from a city to the whole of France, by monitoring point (if the user knows the BSS station code), by monitoring network, or by hydrogeological characteristics if available. An advanced search mode permits the selection of optional criteria so as to specify the desired research, by defining the measurement period, producer, status and data quality. For the latter, a parameter and a value range can be indicated, for example by searching for all stations in a given region where a particular pesticide has been analysed, or for those stations where nitrate content has exceeded 50 mg/L at least once. Search results can be displayed as a map or as a table listing.

The user can then generate a descriptive sheet of the water point, view the data in graphs or tables, and access statistical elements about the data. In addition, all searches can be saved for later use. This system makes it possible to quickly reproduce a search with specific criteria, so as to obtain updated or new data or metadata. Between 2016 and 2020, annual visits to sites averaged almost 105,100. In 2020, nearly 122,000 visits were recorded.

The data can be downloaded from the website either in synchronous mode for data relating to a single water point, or in asynchronous mode for requests concerning several points. The file is deposited on an HTTPS accessible space for a given period. The export contains files describing the data and associated metadata. All files are

in text format. Between 2016 and 2020, annual exports averaged over 31,400. In 2020, nearly 34,000 exports were requested.

4.3 Web services

Several years ago ADES set up web services to access data so as to use them in a variety of tools (geographic information systems, websites, spreadsheets, integration into software, etc.). These web services, which facilitate the use of groundwater information in France, fall into three main categories, which provide:

– permalinks to access specific pages of a website;
– structured access to various data available in ADES—in XML-Sandre—to allow access to the latest available data for reuse in other software, websites, etc. This service follows the standard Sandre monitoring service;
– access to mapping web services that offer interoperable access to water point locations. These services are available in WMS, follow OGC standards, and are in compliance with European Directive INSPIRE requirements. This Directive, developed by the European Commission's Directorate General for the Environment, seeks to establish a spatial data infrastructure for Europe to ensure interoperability between databases and to facilitate the dissemination, availability, use, and reuse of spatial information throughout Europe.

4.4 Web application programming interface, API

The use of national database water data, such as ADES or Naïades, has been boosted by implementation of the

Hub'eau platform services (https://hubeau.eaufrance.fr/). This platform, which facilitates the use of open data on water in France, was set up in 2018 as the result of collaboration between the Office of French Biodiversity (OFB) and BRGM. The Hub'eau platform is a permanent service of the Eaufrance website. The Hub'Eau platform is the solution—in the form of a web API (Application Programming Interface)—for accessing and downloading French water data. Based on its infrastructure and methods suitable for processing and storing massive amounts of data, the Hub'Eau APIs guarantee the best performance in terms of speed and availability (over ten requests per second). The user can thus formulate a request for one or more parameters and use any tool that uses a programming language to collect the results, possibly using a cartographic interface. Results are available in various simple formats (comma-separated, JSON or GeoJSON). This procedure allows rapid access to data in national databases that are regularly enriched and updated. All water level and chemical quality data in ADES are thus accessible via Hub'eau, with a daily update frequency.

The PIC'eau (Potentialising collective intelligence of water data) project makes it possible to do calculations on the data in national databases (https://piceau.brgm.fr). These calculation and data-processing services provide direct access to results, without the need to download the data in advance (data access remains possible). These services, available and documented through APIs, are based on the use of Hub'eau services. PIC'eau offers the following calculations:

– descriptive statistics of water levels and chemical quality);
– trends (water level records and chemical quality) and their significance;
– periodograms (frequency decomposition of a time series);
– data autocorrelation (on temporal or spatial data series).

For each calculation, the user chooses the parameters (period, status, qualification, etc.). Each time one of the services is used, the data are requested from Hub'eau, which ensures that the user has the most complete and up-to-date information. The ADES web site reuses PIC'eau services for the statistical elements made available on the site.

5 Conclusions and perspectives

ADES is a groundwater management tool that responds to management needs at the local level and to priorities dictated by the European Water Framework Directive. The ADES database makes available millions of standardised French groundwater quality and water level records on a public site.

The availability and possible data reuse is of prime importance because multiple studies can be performed using data, without the need to acquire new data. Moreover, certain studies requiring long data histories (sometimes several decades) could not be conducted without these data. Databases such as ADES, which make standardised data freely available, are therefore useful and essential for improving knowledge of groundwater.

Piezometric data is needed for different issues.
They can be used for the following, as examples:

– identify variations in groundwater quantity status, highlighting groundwater response to climate variability [7];
– study linkages between groundwater level variations (for all variability timescales) and large-scale atmospheric circulation [26];
– describe hydrosystems by comparing piezometric data with rainfall and river discharge data [16, 31];
– assess groundwater abstraction limits in unconfined aquifers [2]; and
– build simplified hydrodynamic models such as large-scale groundwater-river exchange models as has been done in France [35].

Quality data makes it possible to assess the following, for example:

– climate change impacts, such as rainfall and temperature variability and drought events, on groundwater quality in different areas of the world, as done, for example by Barbieri et al. or Lasagna et al. in Italy [5, 25] and Fallahati et al. in Iran [14];
– geochemical properties of aquifers such as the Upper Normandy Chalk aquifer [34]; and
– key factors explaining pesticide contamination of groundwater [3].

Ensuring the future sustainability of ADES remains a priority that requires a continued high level of performance. At the same time, it is also necessary to continue improving the system, which, in addition to meeting the needs of the State, must become a federative tool for gathering presently scattered but relevant data. To this end, it will be necessary to offer great flexibility in data storage, for example by allowing the integration of unformatted data that the system must transcribe into standardised data. Similarly, new systems that automatically detect errors will increase the reliability of new and existing data and should include tools for adding value to the data. Such

developments will hopefully be of interest for new producers, whose data will further enrich the database and improve the knowledge of aquifers.

To continue offering services that are increasingly adapted to user needs, ADES will in the future aim to provide groundwater data with new standards, such as SensorThings or OGC API-Features. In 2022, ADES will participate in a Water Quality Interoperability Experiment that will test interoperability and interconnection of the existing Water Quality Data Systems and their use with various OGC service standards. When the database is interoperable, it will be possible to integrate data into international databases such as the EuroGeoSurveys' European Geological Data Infrastructure (EGDI; https://www.europe-geology.eu/). At that point, studies that are larger scale than a single country will become feasible, such as the Hover project (Geoera project; https://geoera.eu), which led to the creation of a European scale map of arsenic levels in aquifers.

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Data availability The datasets analysed during the current study are available in the ADES website repository (www.ades.eaufrance.fr).

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose. The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to participate All authors agree.

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