The Hydrogeological Experimental Site of Poitiers: Hydrogeological versus geophysical investigations

Le site hydrogéologique expérimental de Poitiers : investigations hydrogéologiques et géophysiques

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Abstract. The University of Poitiers (France) has a Hydrogeological Experimental Site (HES) built near the Campus for the sole purpose of providing facilities to develop long-term monitoring and experiments investigating the water and mass transfer processes. The site has been investigated by conventional hydrogeological surveys including flow and temperature measurements, pumping and slug tests. The site was also subjected to geophysical investigations both in surface (3D seismic) and in wells (vertical seismic profile (PSV) and acoustic logging). The paper presents an overview of the different field experiments and shows their relative contribution to knowledge of the karstified Dogger limestones of the Poitou threshold.

Résumé. L'Université de Poitiers (France) dispose d'un Site Hydrogéologique Expérimental situé à proximité du Campus dans le seul but de développer des activités de surveillance et d'expérimentation à long terme des processus de transfert d'eau et de masse. Le site a fait l'objet d'études hydrogéologiques conventionnelles, incluant des mesures de débit et de température, des tests de pompage et d'interférence. Le site a également fait l'objet d'investigations géophysiques à la fois en surface (sismique 3D) et en puits (profil sismique vertical (PSV) et diagraphie acoustique). L'article présente une vue d'ensemble des différentes expériences et montre leur contribution relative à la connaissance des calcaires karstifiés (Dogger) du seuil du Poitou.

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Introduction

The University of Poitiers (France, figure 1a) has a Hydrogeological Experimental Site (HES) built near the Campus for the sole purpose of providing facilities to develop long-term monitoring and experiments investigating the water and mass transfer processes.

The Poitiers Experimental Hydrogeological Site (SEH) was developed by the HydrASA team as part of the Network of National Hydrogeological Sites (SNO H+), under the Poitou-Charentes Region's "WATER" program (CPER 2002-2006).

Located 2 km east of the Science Campus of the University of Poitiers, the SEH occupies an area of 12 hectares on land belonging to the University (Deffend Site: Regional Plant Heritage Botanic Garden). From the geological viewpoint the SEH occupies the north flank of the "Poitou threshold", a huge Mesozoic carbonate plateau marking the transition between the Aquitaine and Paris sedimentary basins (figure1b) [1]. The Jurassic limestone, which overlies a Hercynian crystalline basement, includes two superimposed aquifers: (i) the Lower and Middle Lias Aquifer (5 to 10 m thick). and (ii) the Dogger Aquifer (100 m thick). The two aquifers are separated by the marly Toarcian aquitard (20 m thick).

Studies conducted at the HES focus mainly on the Dogger Aquifer. The site has been investigated by conventional hydrogeological surveys. The site was also subjected to geophysical investigations both in surface and in wells. On the site 35 boreholes have been drilled. The paper presents an overview of the different field experiments and shows their relative contribution to knowledge of the experimental site.

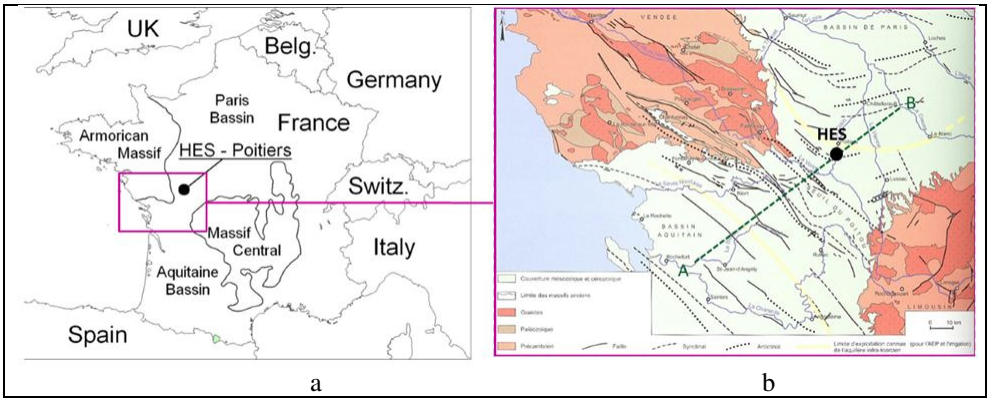


Fig. 1. Hydrogeological Experimental Site (HES): localization (a), geological context(b).

1 Lithology

35 boreholes, including two vertical and two inclined cored boreholes, were drilled on the site in two separate campaigns: 2002-2003 and 2004 (figure 2a). All the boreholes are crossing completely the Dogger Aquifer (depth of boreholes = 125 m). Most of them were drilled on a regular 210 x 210 m grid. The borehole repartition has been done to represent "five spots", with variable mesh size, currently used for hydraulic testing, as shown in figure 2b. Usually, a "five spot" is a square with a production well in the center and injection wells located at each corner of the square.

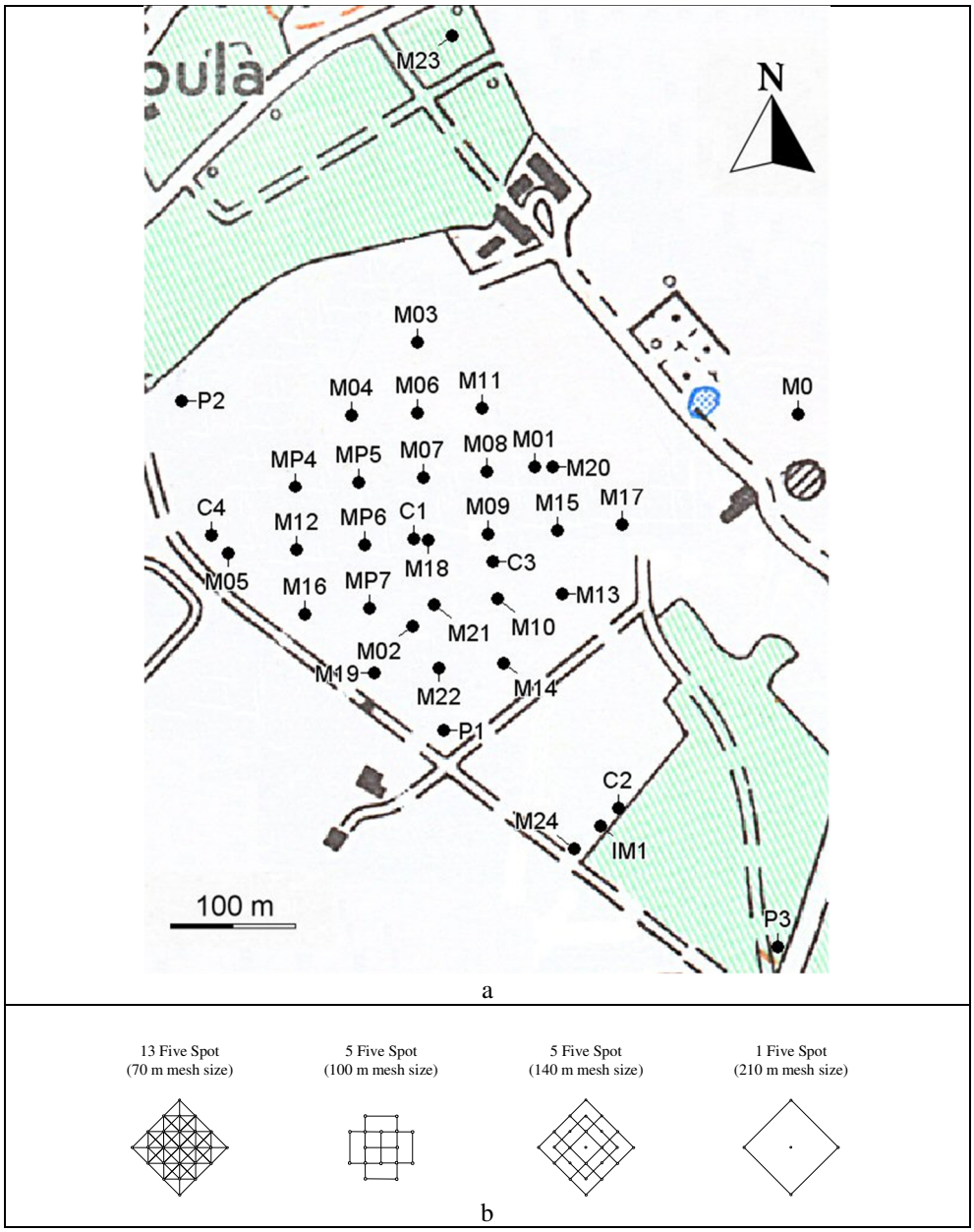


Fig. 2. Borehole location (a) and five spot pattern (b).

HES boreholes are either not cased or are equipped with perforated casing over the full thickness of the Dogger Aquifer. The piezometric level in boreholes therefore represents the average hydraulic head over the thickness of the aquifer. Under natural flow conditions the piezometric levels vary from 15 m to 25 m below the ground surface. During drilling, dry argillaceous limestones were continuously observed to a depth of about 30 m, indicating that the Dogger Aquifer is confined under this relatively impermeable formation. Two additional boreholes were drilled into the crystalline bedrock (boreholes C2 and IM1, about 160 m deep) to be able to record the hydraulic heads in the Lower and Middle Lias Aquifer while hydraulic testing was being conducted in other boreholes. No disturbance of the levels was ever observed in the Lower and Middle Lias Aquifer, demonstrating that the two aquifers are indeed isolated from each other by the Toarcian marls.

Cores obtained during the drillings of boreholes C1 and C2 have been used to measure petrophysical parameters such as porosity (figure 3). It has been shown that the matrix porosity of the limestones varies between 2 and 25 % with an average value of 14 %. Cores and cuttings have been analyzed to define accurate lithologic and stratigraphic columns (figure 4) [2].

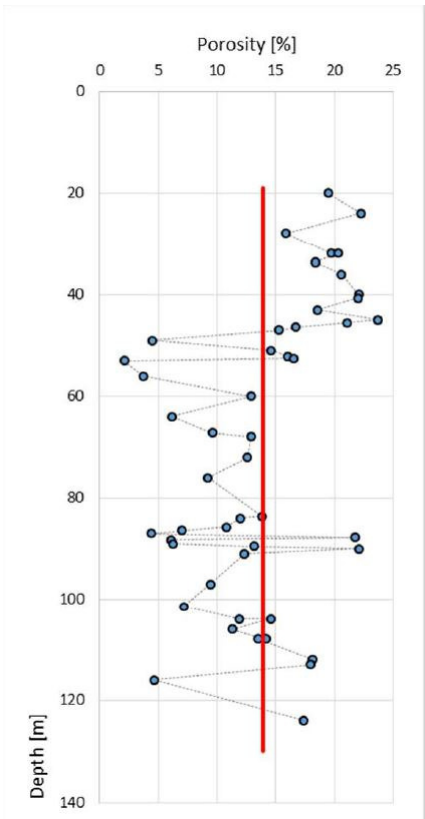


Fig. 3. Porosity from cores. After [2].

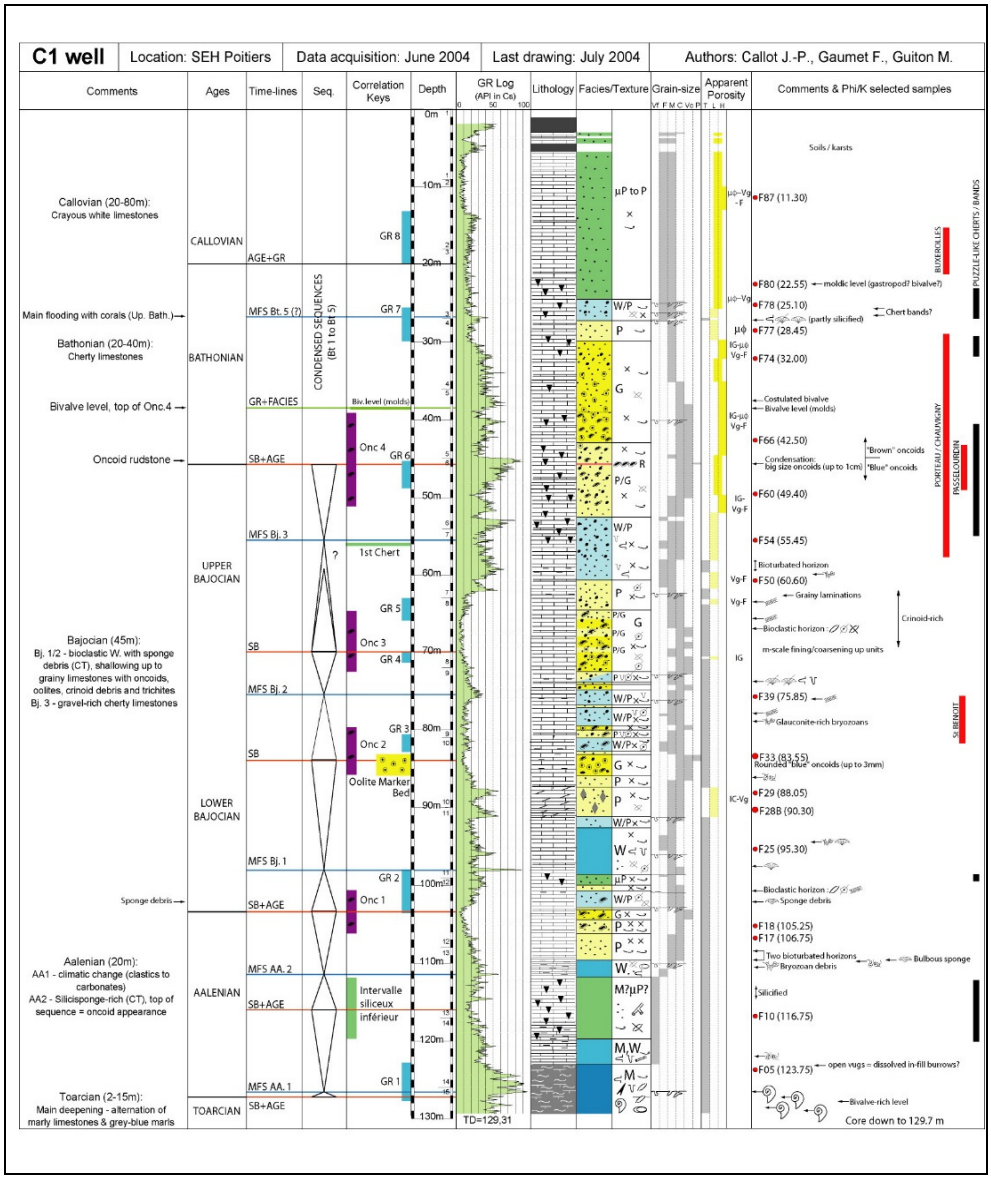


Fig. 4. Lithology from cores and cuttings. After [2].

2 Hydrogeological investigations

Conventionally, hydrogeological investigations concern hydraulic testing such slug test and pumping test. They also concern hydraulic measurements such as flows and temperature.

2.1 Pumping test

It classically consists of pumping a well at constant flow rate and monitoring over time the head drawdown responses at distant wells. The objectives are to determine the hydrodynamic characteristics of the aquifer: transmissivity/hydraulic conductivity and storage coefficient/ compressibility.

Example of pumping test is shown in figure 5. Colours are used to indicate well behaviours (figure 5a). The pumping well and the reinjection well are represented by blue dots. Black dots represent the wells strongly connected to the main karst network. Red dots represent the wells not connected to the karst network. Figure 5b shows the drawdown versus time curves of all the wells. The black curves are associated with wells strongly connected to the karstic network.

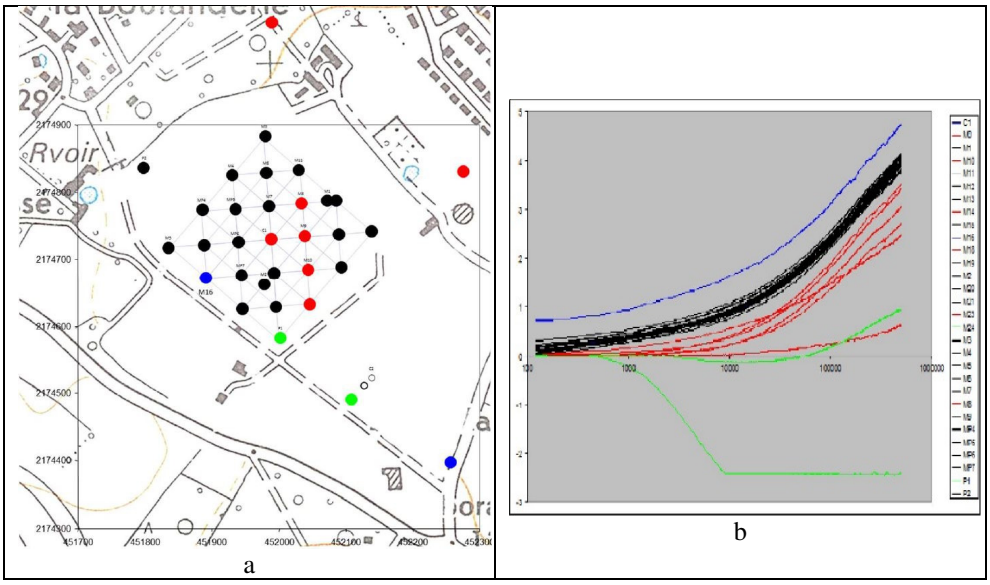


Fig. 5. Example of pumping test: borehole behaviors indicated by colors (a), drawdown curves (b). The black dots and the black curves are associated with wells strongly connected to the karstic network.

2.2 Slug test

A slug test is a particular type of aquifer test where water is quickly added or removed from a groundwater well, and the change in hydraulic head is monitored through time, to determine the near-well aquifer characteristics.

It is a method used by hydrogeologists and civil engineers to determine the transmissivity-hydraulic conductivity of an aquifer. The slug of water can either be added to or removed

from the well — the only requirement is that it be done as quickly as possible (the interpretation typically assumes instantaneously), then the water level or pressure is monitored. Depending on the properties of the aquifer and the size of the slug, the water level may return to pre-test levels very quickly (thus complicating accurate collection of water level data).

Figure 6 is an example of a slug test carried out on the well M19. The changes in hydraulic head versus time observed on the nearby wells (M16, P1, MP7, M22, MP6, M21) are displayed in figure 6a.

The slug test shows that the wells MP7 and P1 are not directly connected to the well M19. On the other hand, the well MP6 shows oscillations due to the injection of water into M19. MP21 and MP22 seem to be strongly connected to M19. By repeating these operations on various wells of the experimental site, a map of connectivity between wells can be elaborated as shown in the figure 6b.

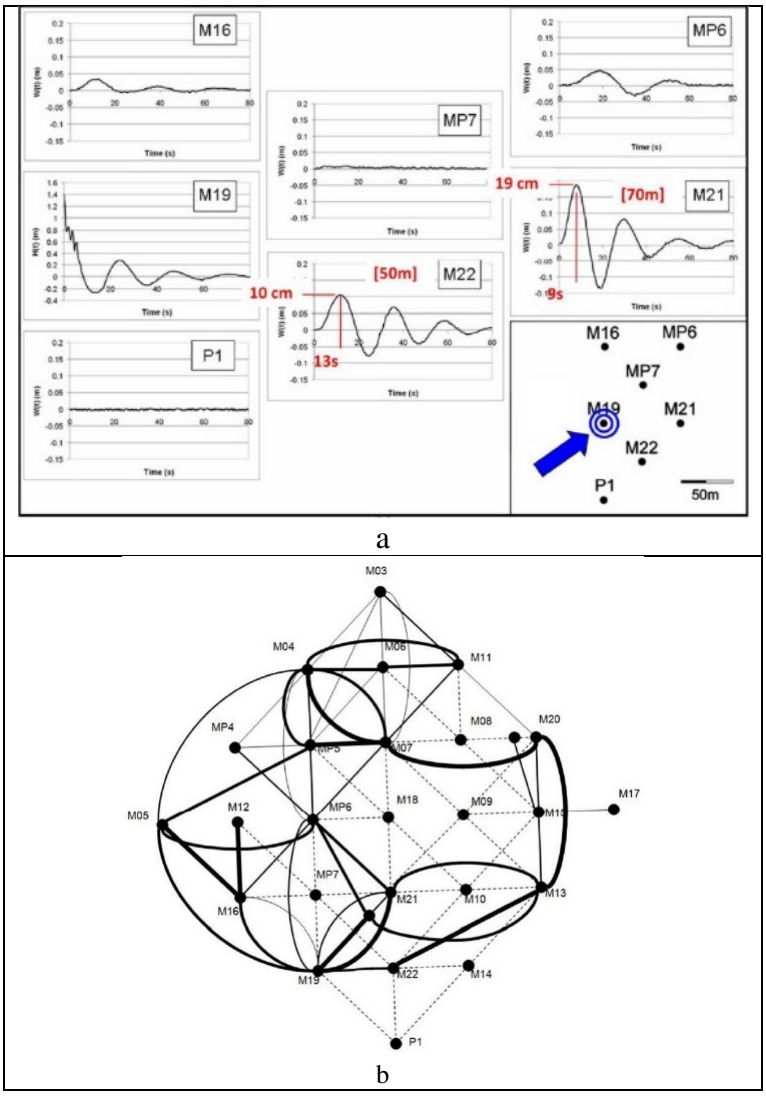


Fig. 6. Example of slug test (a) and connectivity map (b).

2.3 Hydraulic measurement: temperature

A GFTC logger records logs which show the evolution of the Gamma radiation (G), the water velocity (F), the water temperature (T) and the electrical conductivity of the water (C) as a function of depth.

Temperature logs are carried out in the wells to detect any anomalies linked to water intakes in the borehole. Figure 7 shows temperature logs recorded in wells M8 and M13. For well M8, the temperature increases steadily with the depth. The increase is consistent with the regional geothermal gradient, which is about 2,5 degrees per 100 meters. For well M13, the temperature log shows abrupt variations about 60 and 85 meters deep. These variations are likely related to water intake.

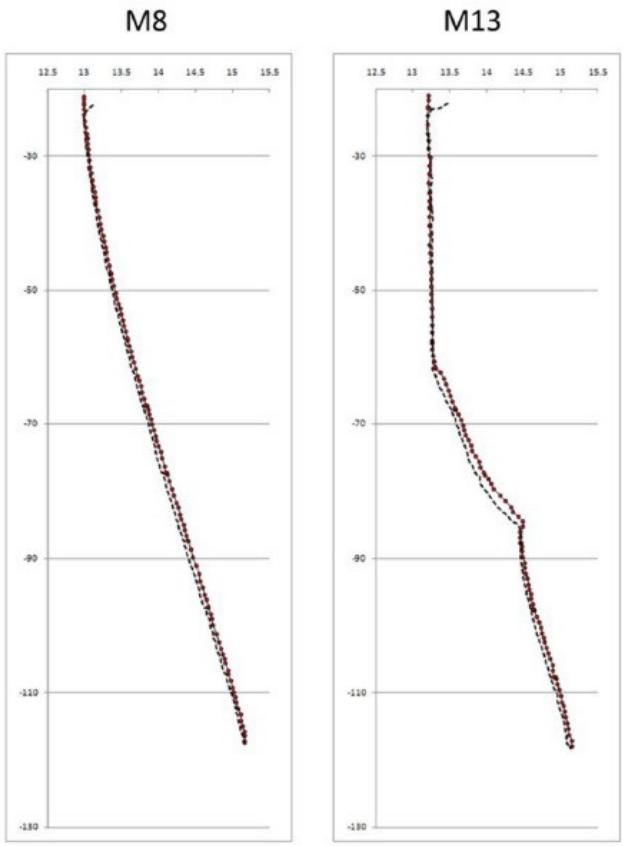


Fig. 7. Examples of temperature logs.

2.4 Hydraulic measurement: flow

Recording the vertical velocity of the water makes it possible to determine the direction of flow circulation in a borehole (upward or downward flow, figure 8). The type of experimentation can be carried out under static conditions.

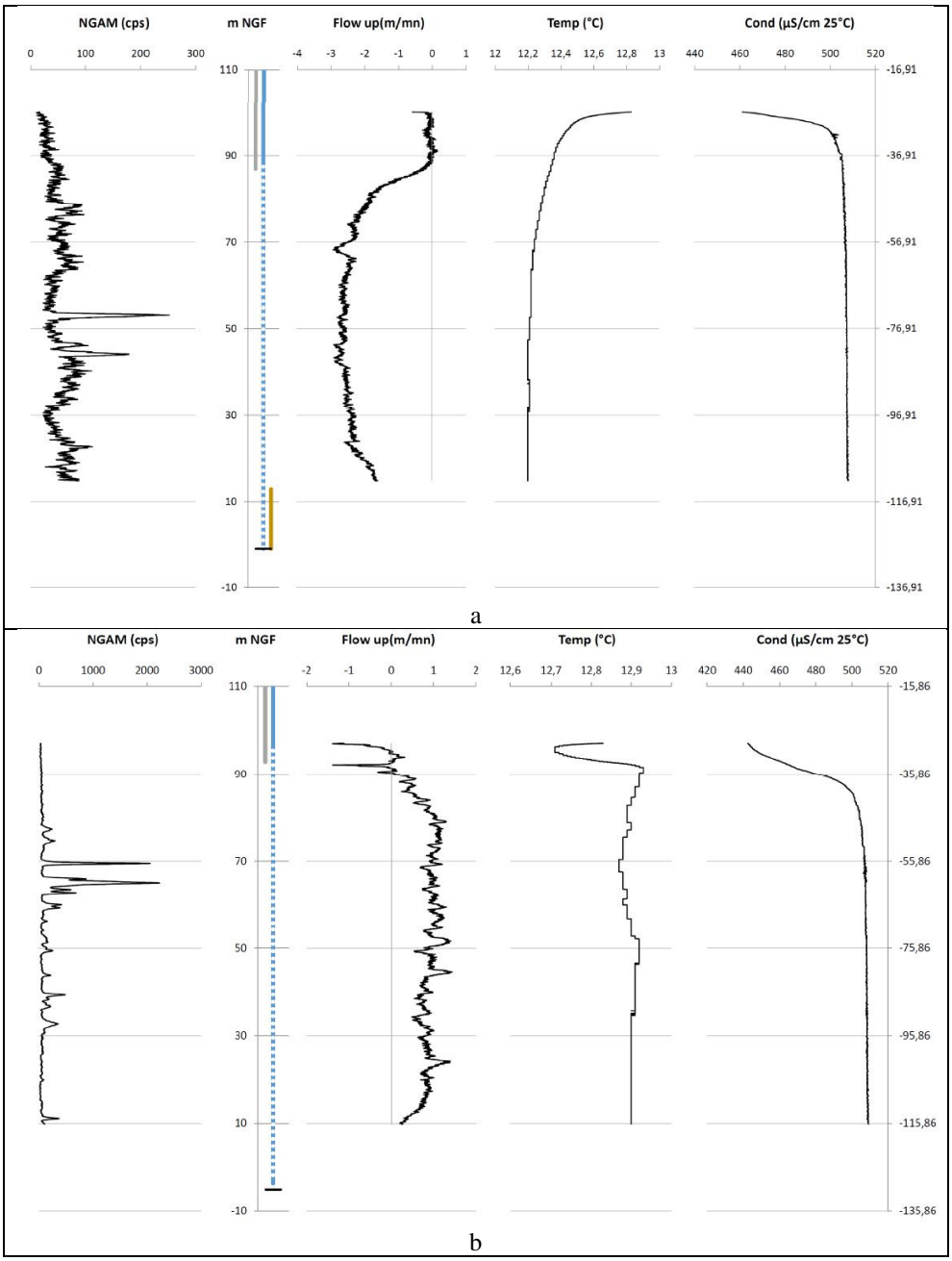


Fig. 8. Examples of flow logs obtained under static condition: downward flow (a), upward flow (b) From left to right: gamma ray, flowmeter, temperature, conductivity.

The measurement of vertical velocity can also be carried out in dynamic conditions, either by pumping in the monitored well, or by pumping in a well offseted from the well being monitored. The experiment makes it possible to know precisely the depths of the producing levels placed in direct relation with the producing levels of the pumping well. The depths of the producing levels identified in the monitored well are used to inject tracers.
Figure 9a shows an example of flowmeter test performed in M07 well with pumping in M06. The flow log shows a downward flow between 35 and 88 meters, where the flow enters into the formation, also visible both on temperature and conductivity logs. Thus, on the well M07, the tracer must be injected at 88 meters depth (green curve). An injection above (84.5 meters, blue curve) or deeper (91.5 meters, red curve) shows a time lag of the tracer due to the time spent in the injection drilling (Figure 9b).

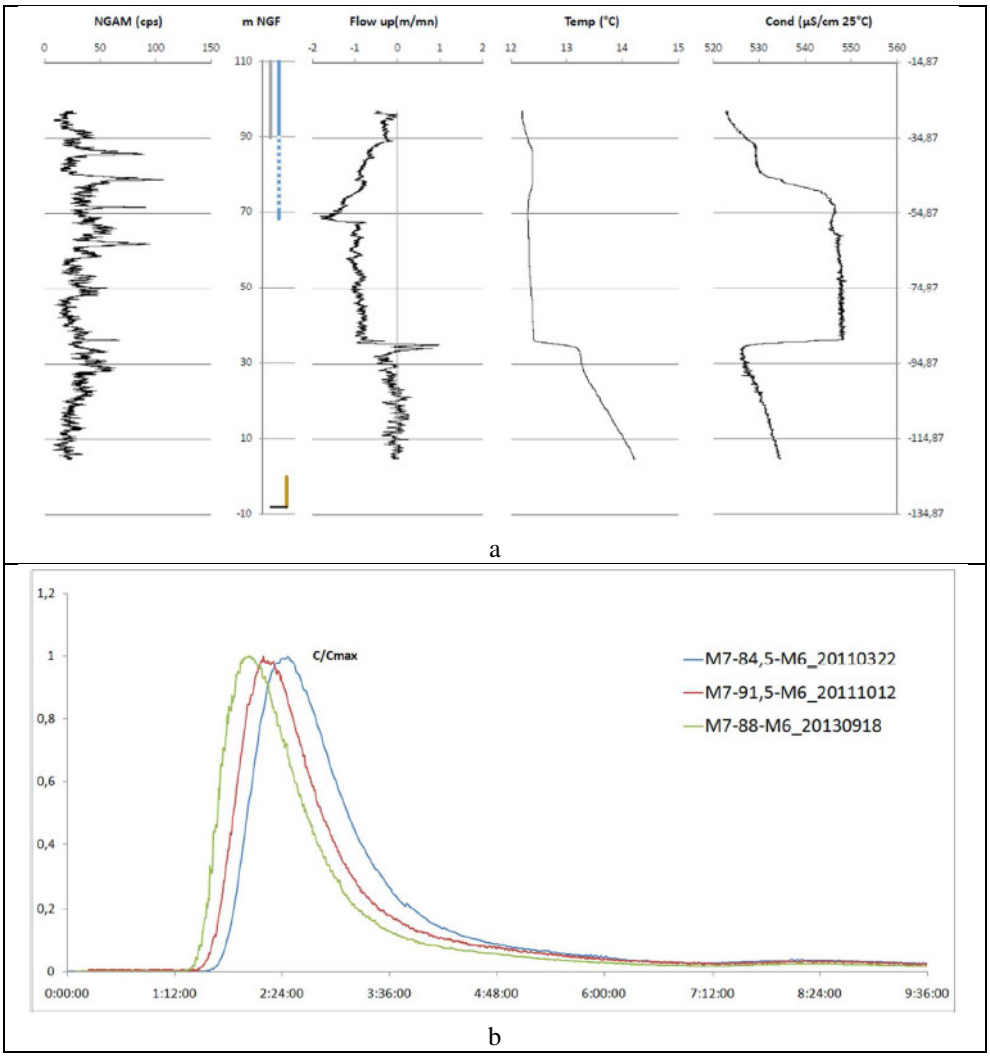


Fig. 9. Flow log obtained under dynamic condition in borehole M07 with pumping in M06 well.
a: from left to right: gamma ray, flowmeter, temperature, conductivity observed in M07 well.
b: breakthrough curves observed in M06 well after injection of the tracer in M07 at depths: 84,5 m (blue curve), 88 m (green curve) and 91,5 m (red curve).

3 Geophysical investigations: 3D survey

At the HES in all the boreholes, Long Normal resistivity tools have been run to obtain the resistivity of the formation. All the resistivity logs, run in two orthogonal lines of boreholes (North-South and East-West), show the same significant peak of resistivity at a depth around 110 meters (figure 10). These observations lead us to conclude that the stratigraphy is nearly horizontal with a very small dip of 1 degree in the West direction. Consequently, on the site, there is no tectonic features with vertical displacement. This observation is confirmed by a 3D survey conducted to obtain a 3D seismic block.

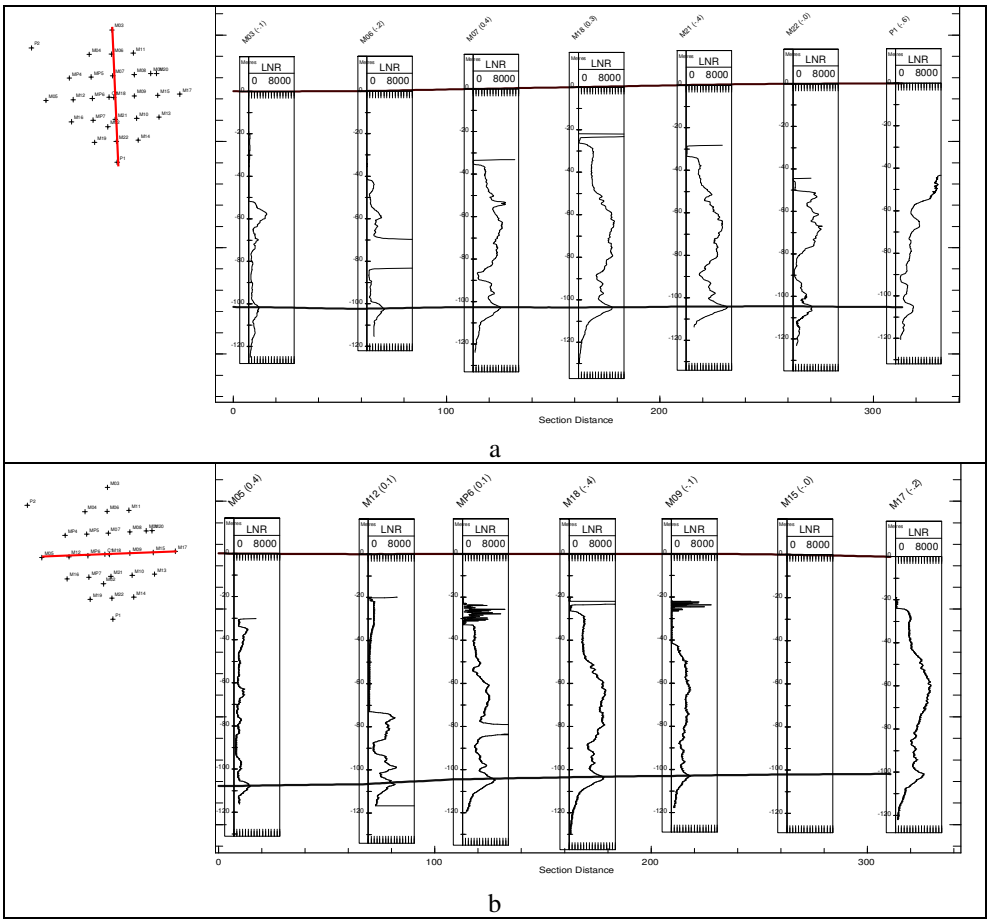


Fig. 10. Resistivity logs oriented in two orthogonal lines: North-South (a) and East-West (b).

Usually, 3D seismic imaging requires a great amount of data and powerful computer. On the Hydrogeological Experimental Site, a 3D survey has been designed to obtain a 3D cube by recording a low amount of data [3, 4]. The complete survey is composed of 20 receiver lines (in line direction) with a 15 m distance between adjacent lines. Each line is composed of 48 single geophones with 5 m between adjacent geophones.

Figure 11a shows the location of the seismic lines and of the wells. In well C1, a VSP has been recorded to perform the time to depth conversion of seismic data. Acoustic velocity logs, recorded in wells C1, MP5, MP6, M08 and M09, have been used as constraints to convert seismic amplitudes in pseudo-velocities during the inversion process [3, 4].

Arrows in red and green show the in-line extension of the area covered by the 3D survey and the 2D survey. The seismic processing has been done to obtain a 3D distribution of the seismic interval velocities in depth. To quantify the porosity variations within that aquifer, the seismic velocities were first converted into resistivity values. For that purpose, the empirical relationship between seismic velocity and true formation resistivity proposed by Faust was used. Resistivity values were then converted into porosity values, by using Archie's law. Figure 11b shows the velocity and porosity sections associated with cross line 24. The resulting 3D seismic pseudo-porosity block revealed three high-porosity, presumably-water-productive, layers, at depths of 35-40, 85-87 and 110-115 m (figure 12) [4, 5].

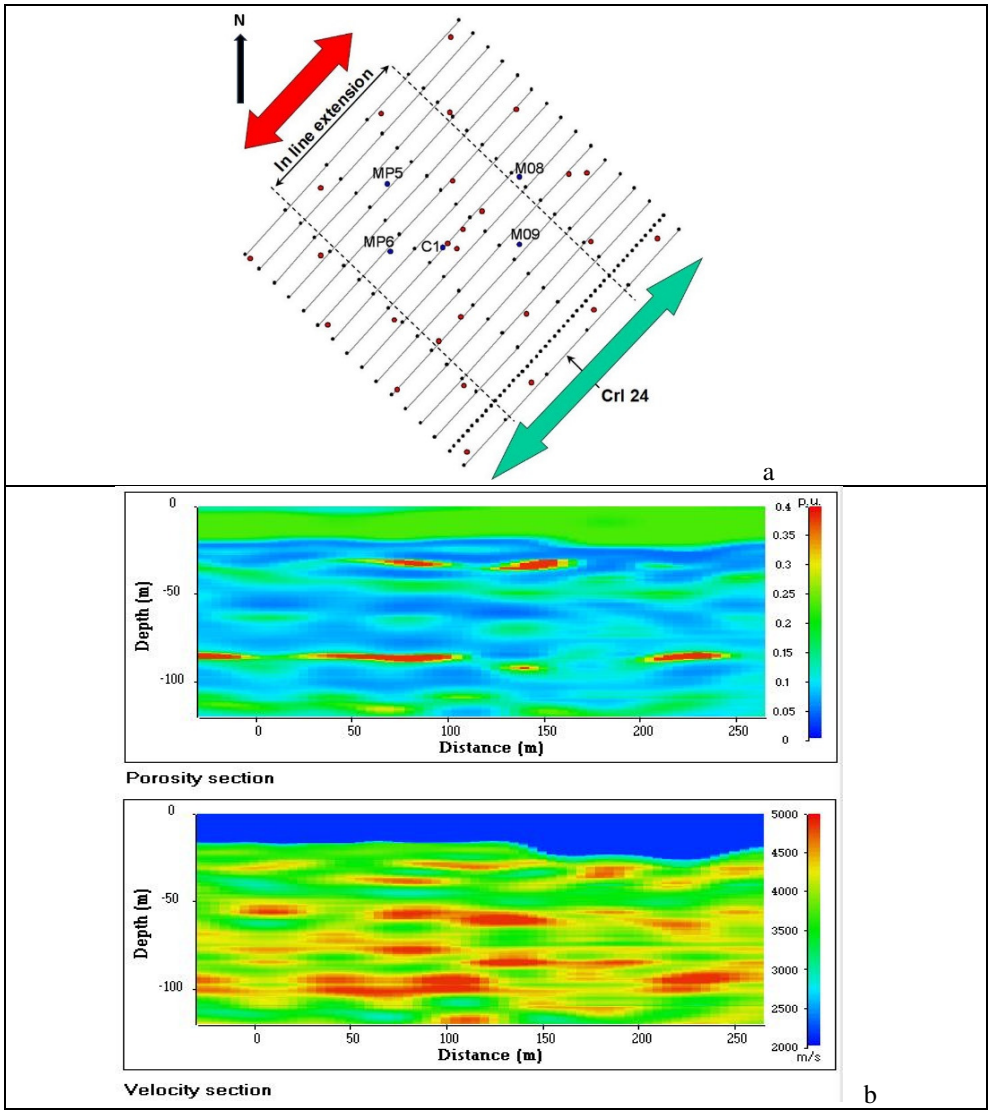


Fig. 11. Location of the seismic lines (a), porosity and velocity sections (b) associated with cross line 24. After [3, 4].

The 85-87 m-depth layer is the most porous one, with bodies of a porosity higher than 30% that represent the karstic part of the reservoir.

4 Borehole Geophysical investigation: VSP and acoustic logging

Full waveform acoustic data and vertical seismic profiles (VSP) with hydrophones have been recorded in boreholes. The two sets of data have been used to evaluate the potential of both the acoustic method in high frequencies (1 to 20 kHz) and VSP's in low frequencies (10 to 150 Hz) to detect karstic bodies and flows.

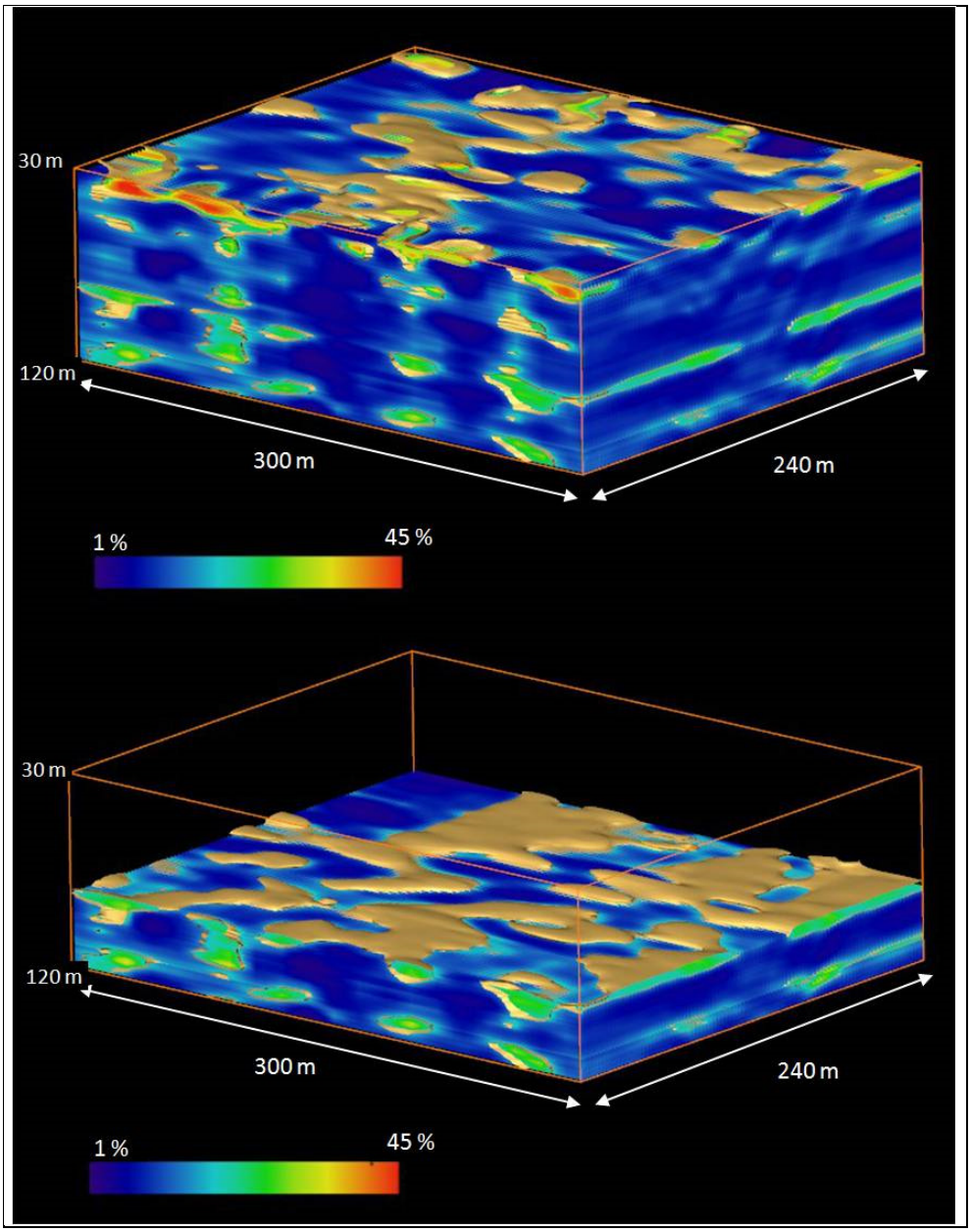


Fig. 12. HES site - pseudo porosity block in the 30 – 120 m depth interval (top) and in the 85 - 120 m depth interval (bottom). After [4, 5].

4.1 Ambient noise and VSP in borehole C1

For VSP acquisition, the seismic source is a lightweight dropper, and the borehole sensor is a hydrophone. The sampling interval in depth is 2.5 m. Before each shot, the ambient noise has been recorded.
If flow circulation introduces some changes in ambient noise properties, the analysis of the ambient noise (figure 13a) has been done to detect the presence of flows. For that purpose, the average and the variance of the amplitude spectrum of each noise trace have been computed. We have noted that an ambient noise factor defined as the average to variance ratio increases significantly at the level of karstic bodies.

The VSP is highly corrupted by Stoneley waves (tube waves).Conversion of down going P-wave in down and up going Stoneley waves have been observed at the level of the karstic bodies. This phenomenon occurs in highly permeable formations. We can note that the first arrival which is the down going P wave is strongly attenuated at 60 m depth (figure 13b). At that depth, the P-wave is partly converted to a down going Stoneley wave which is reflected at the bottom of the well.

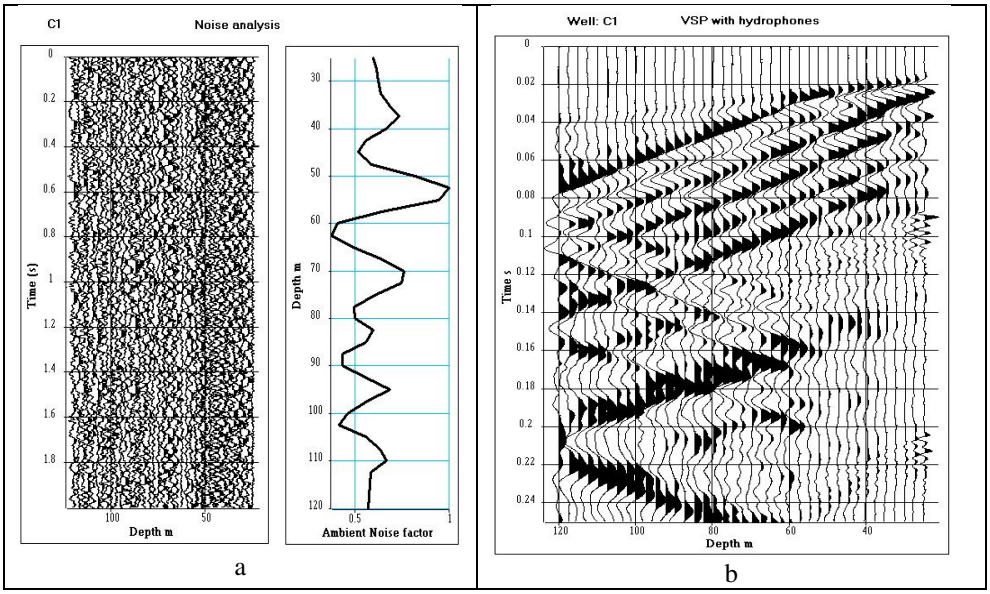


Fig. 13. Ambient noise (a) and VSP (b) recorded in borehole C1.

The VSP data have been processed to extract the down-going and up-going Stoneley waves.

Figure 14 shows the amplitude variation of the upgoing Stoneley waves. We can notice a phenomenon of conversion at a depth of 57m. The instantaneous amplitudes of the upgoing converted Stoneley waves have been stacked in a small corridor located after the arrival time of the downgoing P-wave, in order to obtain a body-wave to Stoneley wave conversion factor which points out a karstic level at a depth of 57m.The analysis of the ambient noise shows that the variations of the ambient noise factor are correlated with the level of conversion of P-wave in Stoneley waves. The attribute, named VSP flow index, defined as the product of the ambient noise factor by the body wave to Stoneley wave conversion factor has been used to detect both karstic bodies and flow.

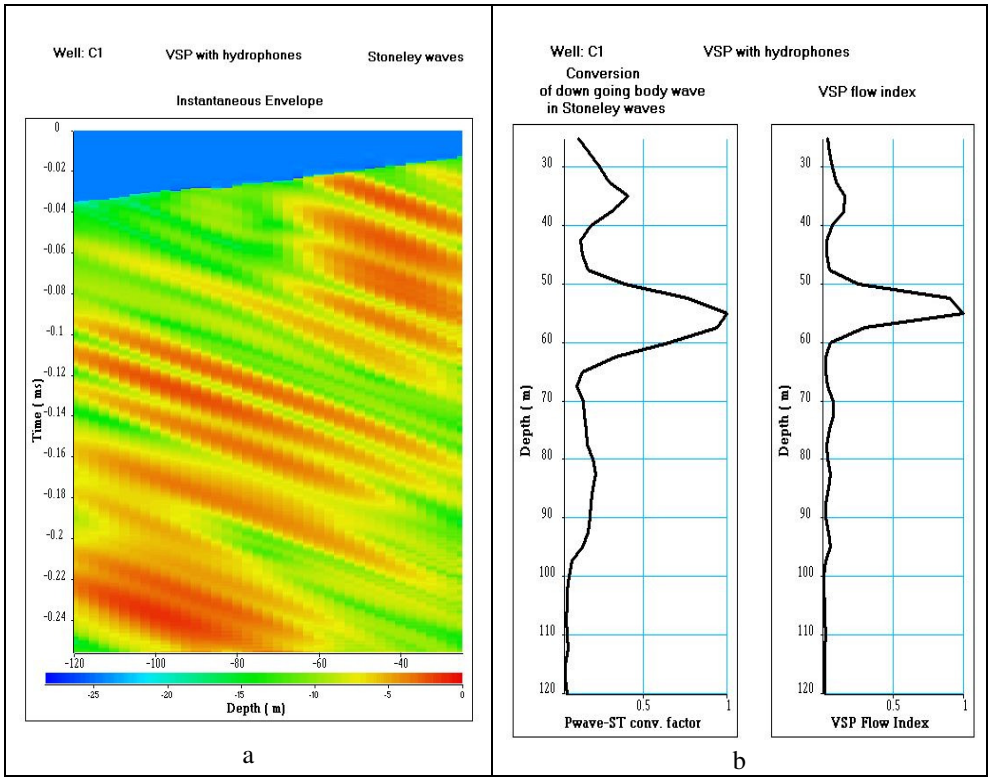


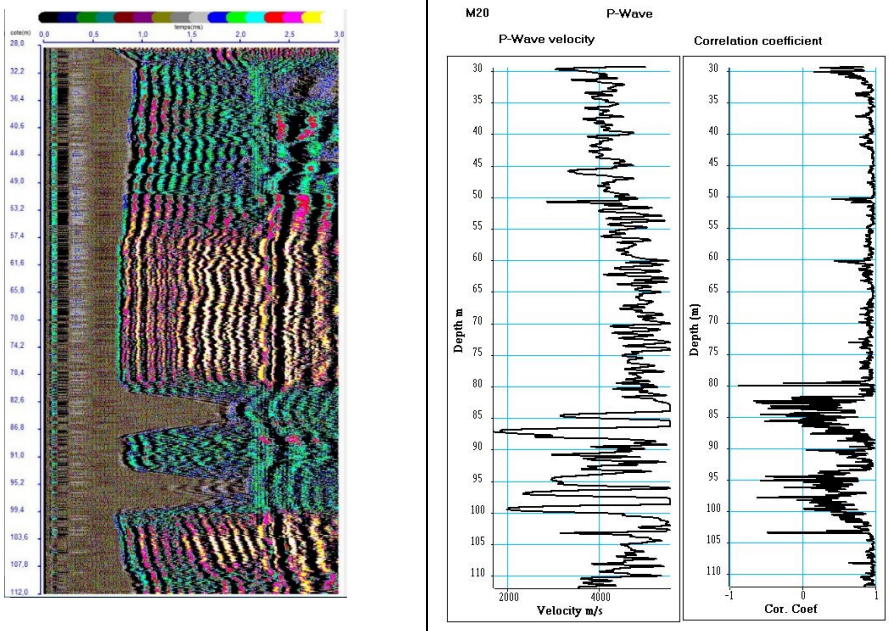
Fig. 14. Upgoing Stoneley waves - instantaneous amplitude (a) and VSP logs: conversion factor and flow index (b).

4.2 Acoustic logging in borehole M20

The transmission of an acoustic wave through geological formations is used for formation characterisation. Monopole-type tools are the most used. Sources and receivers are multidirectional. The acoustic tool used for the field experiment is a flexible monopole tool with two far offset receivers R1 and R2. The offset between the source and the receiver R1 is 3 meters. The distance between the two receivers is 25 centimeters. The sample interval in time is 5 microseconds and the recording time is 5 milliseconds. The sample interval in depth is 5 centimeters. Sources generate in the fluid a compression wave which creates in the formation a compression wave and a shear wave at the refraction limit angles.

On the section (figure 15a), we can observe five propagation modes:

- Refracted P-Wave between 0.7 and 1.2 millisecond
- Converted refracted S-wave followed by Rayleigh waves between 1.3 to 2 milliseconds
- High frequency fluid waves after 2.1 milliseconds
- Low frequency dispersive Stoneley wave after 2.2 milliseconds



a b

Fig. 15. Acoustic section (a) and acoustic logs: P-wave velocity log and correlation coefficient log (b).

The acoustic data processing which is done to estimate simultaneously the velocity of the formation with its associated correlation coefficient (figure 15b), the amplitude of the acoustic signal and the level of noise. In karstic levels, we usually observe a low velocity of the formation, a low amplitude of the acoustic signal and a low value of the correlation coefficient, as it can be seen in the two depth intervals between 82 and 88 meters and between 95 and 100 meters.

A specific attribute, named Noise Signal detector, has been designed to detect karstic levels. The attribute is the product of 3 normalized terms: an amplitude term (1- Amp(z)/AmpMax, with Amp(z) the acoustic amplitude at depth z and AmpMax the highest acoustic amplitude, figure 16) , a correlation term, and a velocity term (1- VP(z)/VPMax, with VP(z) the P-wave velocity at depth z and VPMax the highest P-wave velocity) [6].

Figure 17 shows from left to right:

- the acoustic noise detector : product of the amplitude term by the correlation term.
- the Noise Signal detector: product of the acoustic noise detector by the velocity term.
- the acoustic flow detector.

Integration versus depth of the Noise Signal detector from bottom to the top of the well has been done to mimic a flow measurement (figure 16).

The Noise/Signal detector highlights two karstic levels at depths of 82 – 85 m and of 93 – 100 m. The two karstic levels, detected by acoustic logging, are confirmed by Optical televiewer (OPTV) logs (figure 18).

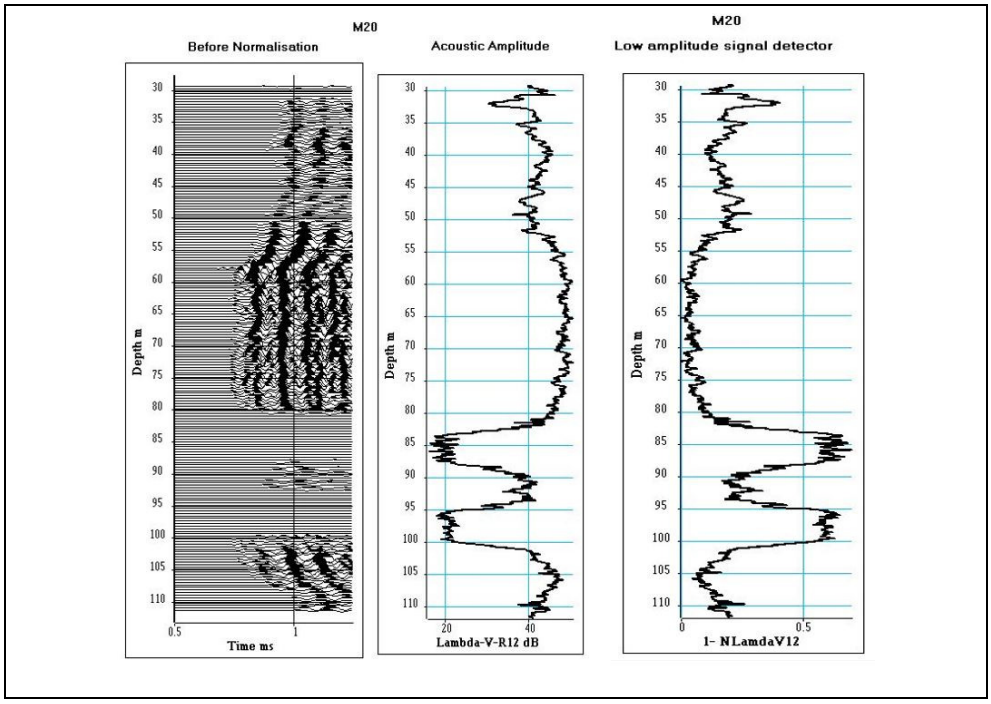


Fig. 16. Acoustic P-waves. From left to right: acoustic section, P-wave amplitude log and amplitude signal detector log (amplitude term).

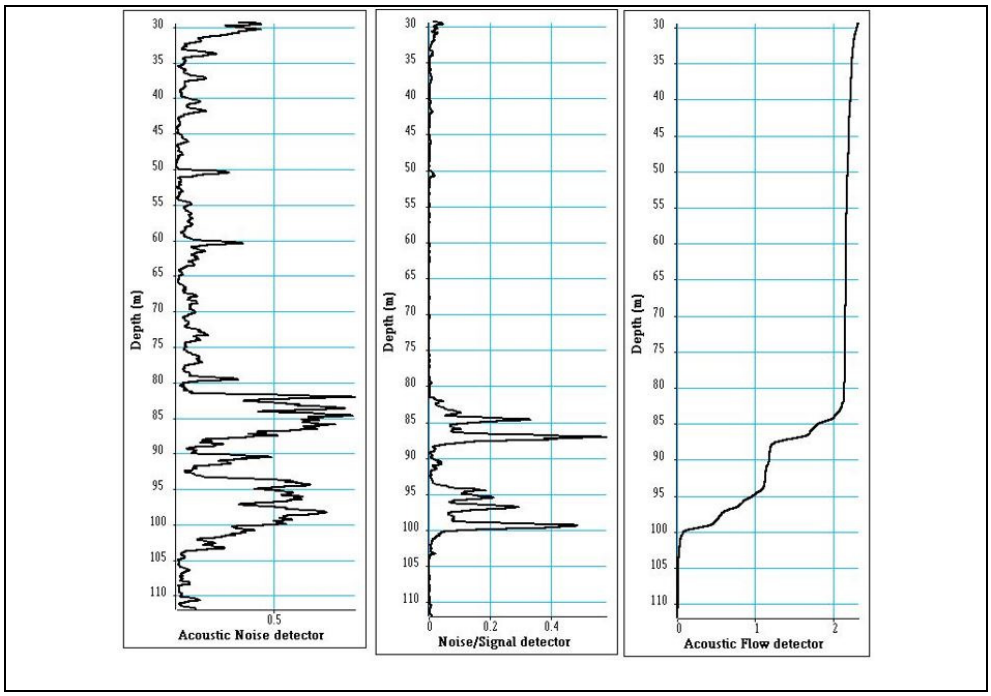


Fig. 17. Karstic body detection and flows with acoustic data (borehole M20).
Acoustic logs (from left to right): noise detector, Noise/Signal detector, acoustic flow detector.
Karstic bodies and flows are detected in the 80 – 90 m and 110 – 115 m depth intervals.

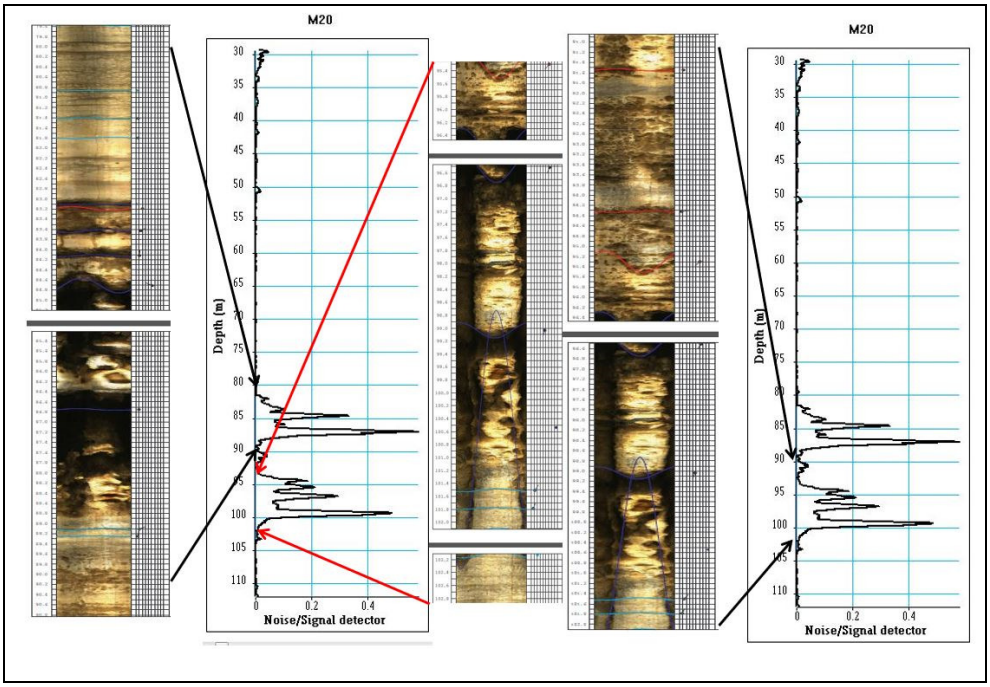


Fig. 18. Karstic body detection: comparison between acoustic Noise/Signal detector and Borehole wall imaging (OPTV).

5 Combined analysis of geophysical and hydrogeological data

Combined analyses of geophysical and hydrogeological data can be carried out locally at wells or on a larger scale using 3D seismic data. These studies are carried out with the aim of detecting the water producing levels at wells and establishing a probable network of karst conduits.

Figure 19 is a synthesis of the procedures developed to analyze acoustic data, ambient seismic noise, VSP data, OPTV and PLT log to detect karstic bodies and flows. The analysis of the acoustic data and the computation of the *Noise/signal detector* have allowed the detection of karstic levels in two depth intervals between 82 and 88 meters and between 95 and 100 meters. The processing of VSP data and the analysis of the ambient noise confirm that the 82.5-100 m depth interval is a karstic layer and detect the presence of flow. A PLT log obtained during a pumping in well M04 (dynamic conditions) validates the results of the acoustic- seismic experimentation.

The information obtained on each well is then merged with inter-well tracing data and 3D seismic data to construct a probable distribution network of karst conduits.

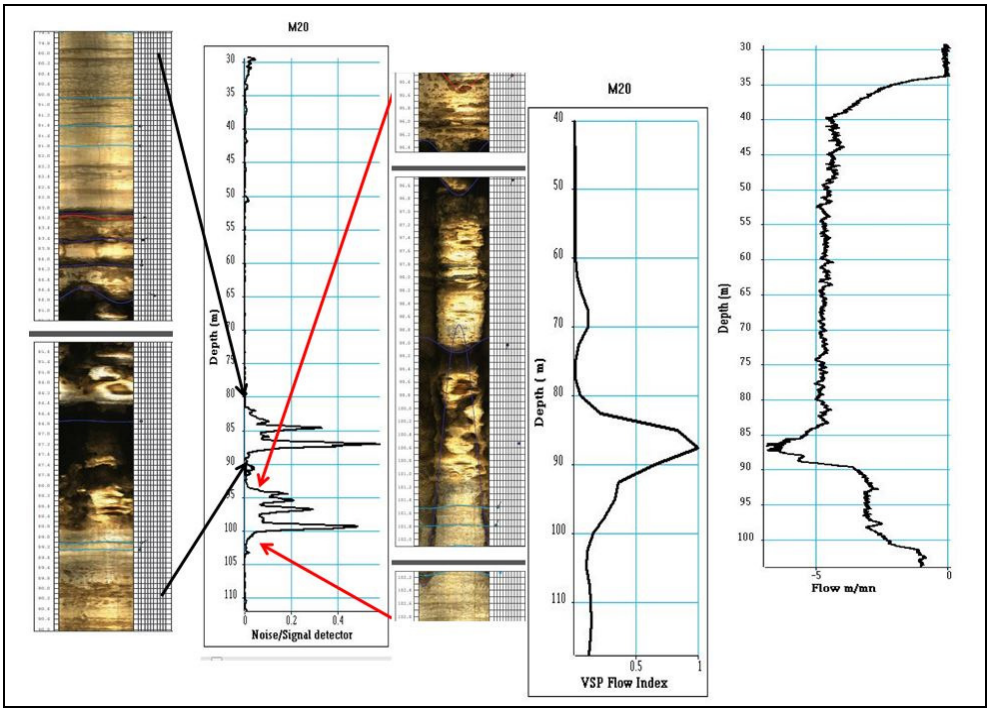
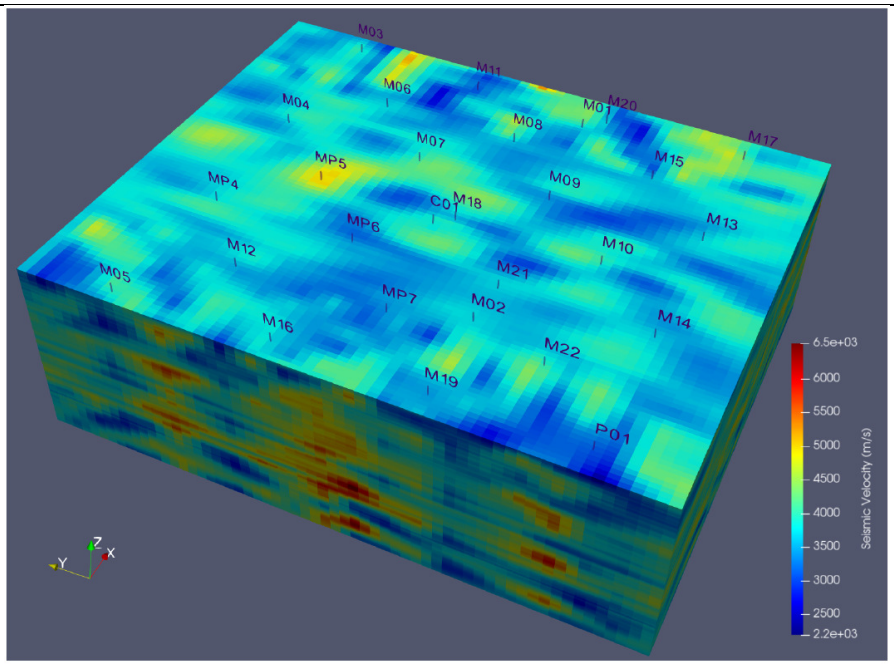


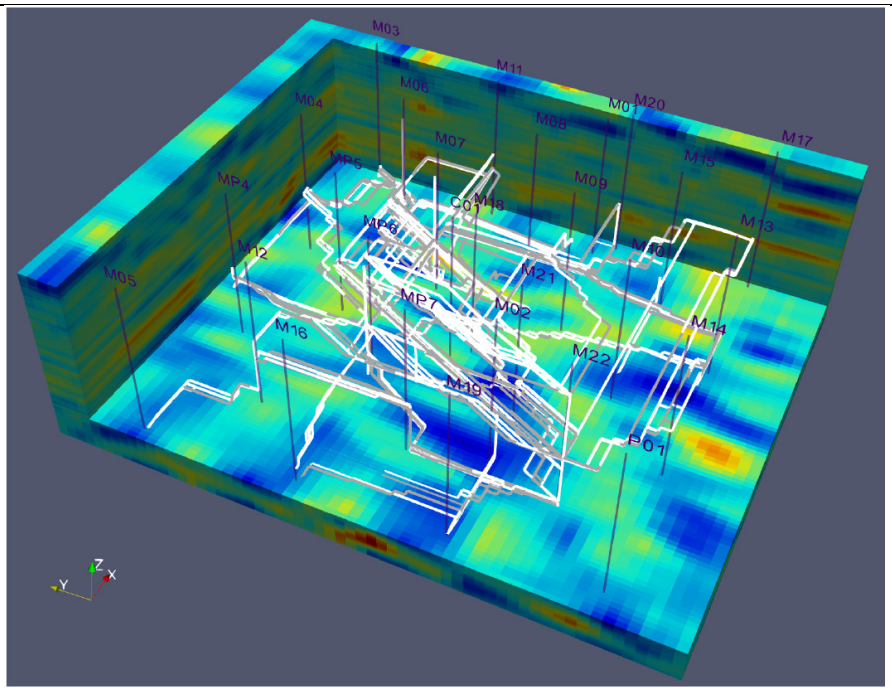
Fig. 19. Detection of karstic levels and flows by acoustic logging (*Noise/Signal detector*), VSP (*VSP flow index*), borehole wall imaging (*OPTV*) and flow measurement under dynamic conditions.

An integrated approach for the identification of effective three-dimensional (3D) discrete karst conduit networks conditioned on tracer tests and geophysical data (3D) has been developed [7]. The procedure is threefold: (i) tracer breakthrough curves (BTCs) are processed via a regularized inversion procedure to determine the minimum number of distinct tracer flow paths between injection and monitoring points [8], (ii) available surface-based geophysical data and borehole logging measurements are aggregated into a 3D proxy model of aquifer hydraulic properties, and (iii) single or multiple tracer flow paths are identified through the application of an alternative shortest path (SP) algorithm to the 3D proxy model. The capability of the proposed approach to adequately capture the geometrical structure of actual karst conduit systems mainly depends on the sensitivity of geophysical signals to karst features, whereas the relative completeness of the identified conduit network depends on the number and spatial configuration of tracer tests.

The applicability of the proposed approach is illustrated in figure 20 which shows the distribution of seismic velocities (figure 20a) and karst conduit network obtained from the combined analysis of inter-well tracer tests, borehole flowmeter logs, and 3D seismic imaging data (figure 20b).



a



b

Fig. 20. Karst conduit network obtained from combined geophysical and hydrogeological data.
a: three-dimensional seismic velocity model of the HES aquifer from 35 to 130 m below the ground surface [4, 7].
b: HES karst conduit network obtained from the combined analysis of inter-well tracer tests, borehole flowmeter logs, and 3D seismic imaging data. The white and gray lines represent the main and secondary paths, respectively [7].

Conclusion

The Hydrogeological Experimental Site (HES) of Poitiers, developed to conduct long-term monitoring and experiments studying water and mass transfer processes, has been investigated by both hydrogeological and geophysical surveys.

The paper has presented an overview of the different field experiments and shown their relative contribution to knowledge of the karstified Dogger limestones of the Poitou threshold.

Considering all the experiments carried out on the hydrogeological site makes it possible to provide a network of karst conduits through different objectives based on the specificities of each field experiment:

- *Identification of water producing level on each well.*
  For that purpose, long normal resistivity, temperature, electrical conductivity and flowmeter logs are recorded. Flowmeters appear to be the most relevant for identifying producing levels. Borehole imaging tools are also run. OPTV gives very high resolution borehole wall images which allows the identification, the localization and the size of geological features such as fractures, vugs, karst conduits. In addition, full waveform acoustic data can also be used to detect geological features and provides the mechanical parameters such as P-wave velocity. Acoustic logs are also used to constrain the inversion of seismic data and to define an index of karst body detection. In the same way, VSP data are used to perform the time to depth conversion of the seismic data and to detect the presence of karstic bodies by analyzing Stoneley waves.
- *3D image of the aquifer reservoir.*
  In the case of karstified limestone aquifers, seismic method is recommended to identify the major karstic levels. The processing of the seismic data is done to obtain 3D seismic block in depth which can be converted into a 3D pseudo velocity block using acoustic velocity logs as constraints during the inversion process and then in a pseudo-porosity block after calibration with borehole data.
- *Hydraulic tests.*
  Cross hole pumping tests must be conducted to detect flow paths. High values of hydraulic diffusion evidenced by slug tests allow to establish connectivity maps. On the HES, the pumping tests allow to differentiate between connected wells and not-connected wells to the karstic network.
- *Tracer tests*
  Tracer breakthrough curves are used to determine the minimum number of distinct tracer flow paths between injection and monitoring points.
- *Combined analyses of geophysical and hydrogeological data*
  These studies are carried out with the aim of detecting the water producing levels at wells and establishing a probable network of karst conduits.

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