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# Qualitative and Quantitative Hydraulic Analysis of Harmonic Pumping Tests for Identifying the Conduits Networks in a Karstic Aquifer

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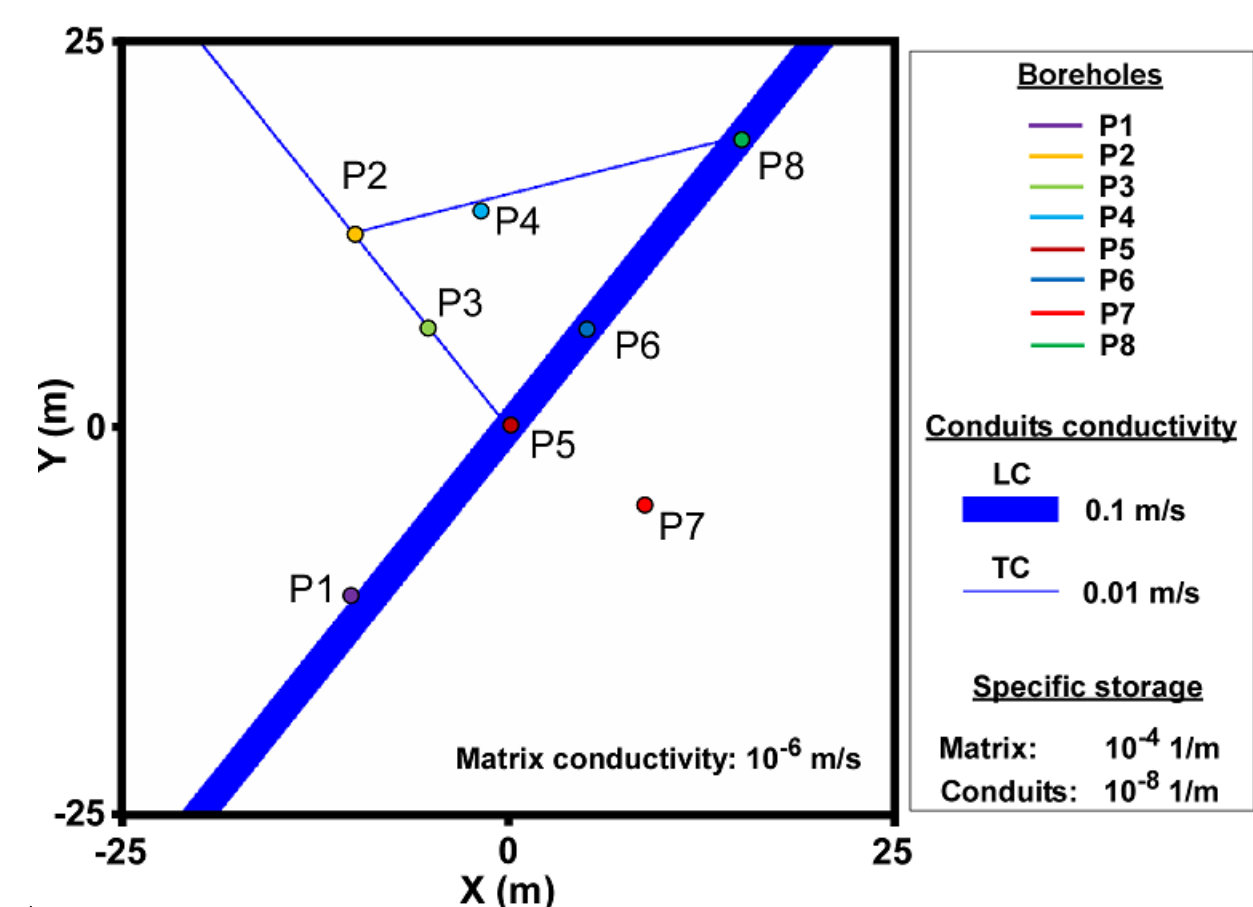
# Qualitative and Quantitative Hydraulic Analysis of Harmonic Pumping Tests for Identifying the Conduits Networks in a Karstic Aquifer

We present a qualitative and quantitative study to understand and interpret the information carried by the responses to harmonic pumping tests performed with different frequencies in a karstic aquifer. This study is first led theoretically on a synthetic case, then on an application case on a karstic field at a decametric scale.

## SYNTHETIC CASE (Qualitative study) Article Fischer et al. *Journal of Hydrology* 2018 [1]

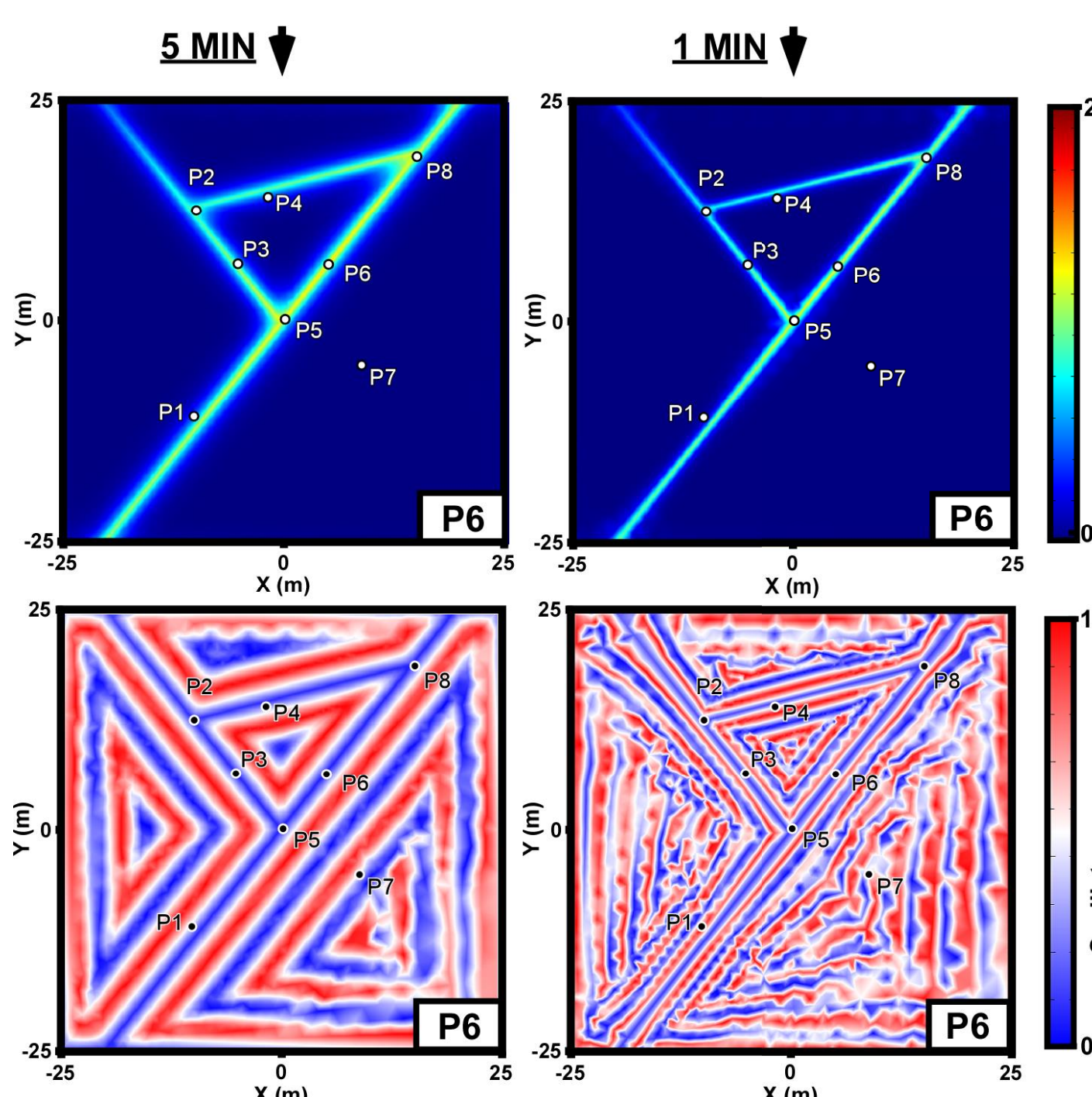
### Synthetic model

We have studied the theoretical responses generated by harmonic pumping tests in a 2D synthetic model in a frequency domain (fig. 1). This model represents a simple discrete karstic network in a matrix continuum investigated through 8 boreholes spatially distributed. The model simulates the amplitude and phase offset responses to harmonic pumping tests led for different periods of oscillatory signals.



▲ (fig.1) Presentation of the synthetic model.

### Simulations (Example of pumping in P6)

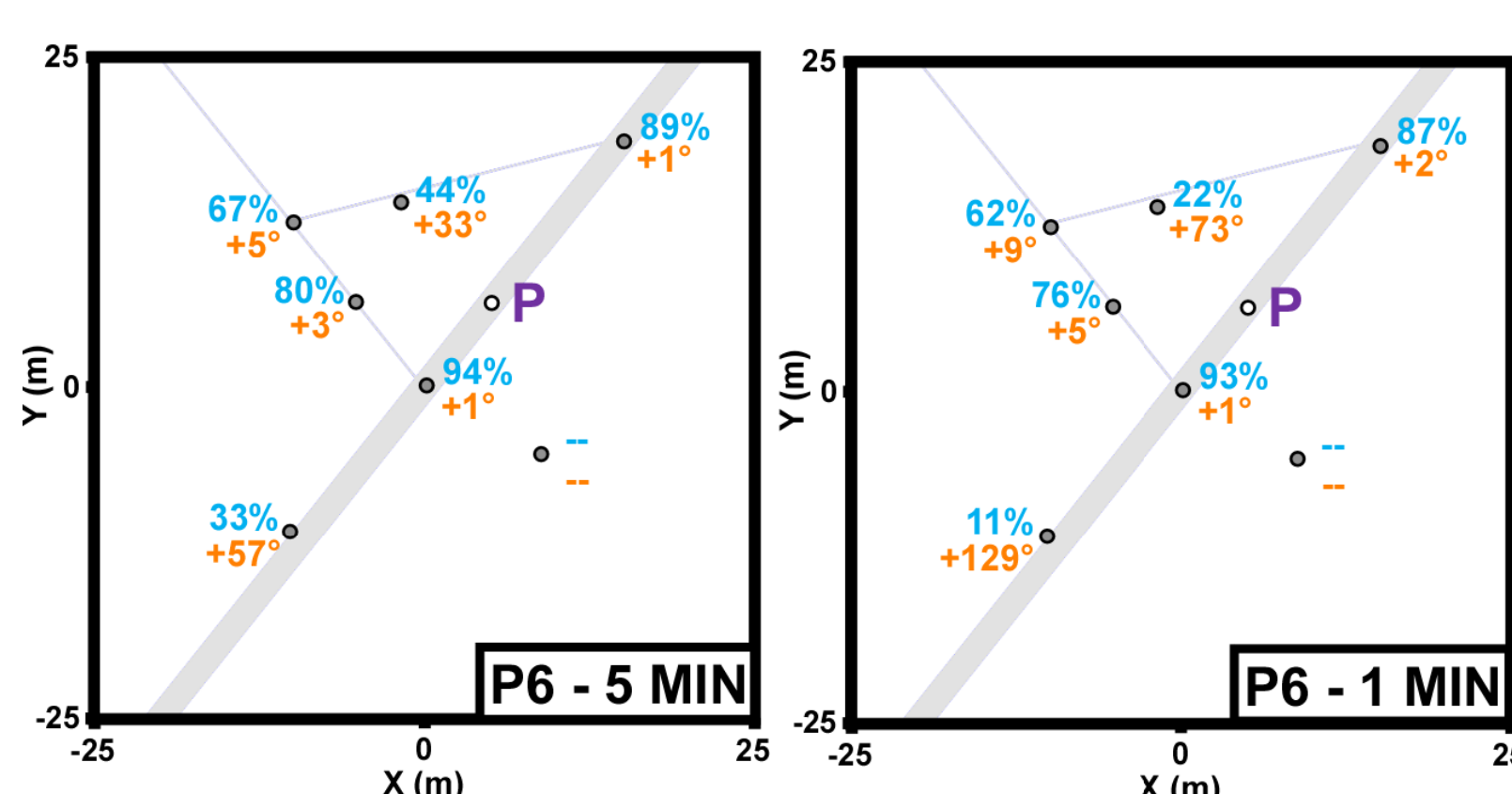


▲ (fig.2) Simulated maps of amplitudes and phase offsets for different periods (1 and 5 min).

The simulations of the model (fig. 2) permit to distinguish 3 type of responses:

- Conduit connectivity response (high amplitude and low phase offset),
- Matrix connectivity response (negligible amplitude),
- Dual connectivity response (variable amplitude and phase offset) associated to points in the matrix but near the conduits.

The behavior of the 'dual' responses varies with the period of signal (P1 and P4 in (fig. 3)). Thus, different periods of signal permit to extract different information from the responses, especially for points located at the interface conduit/matrix.

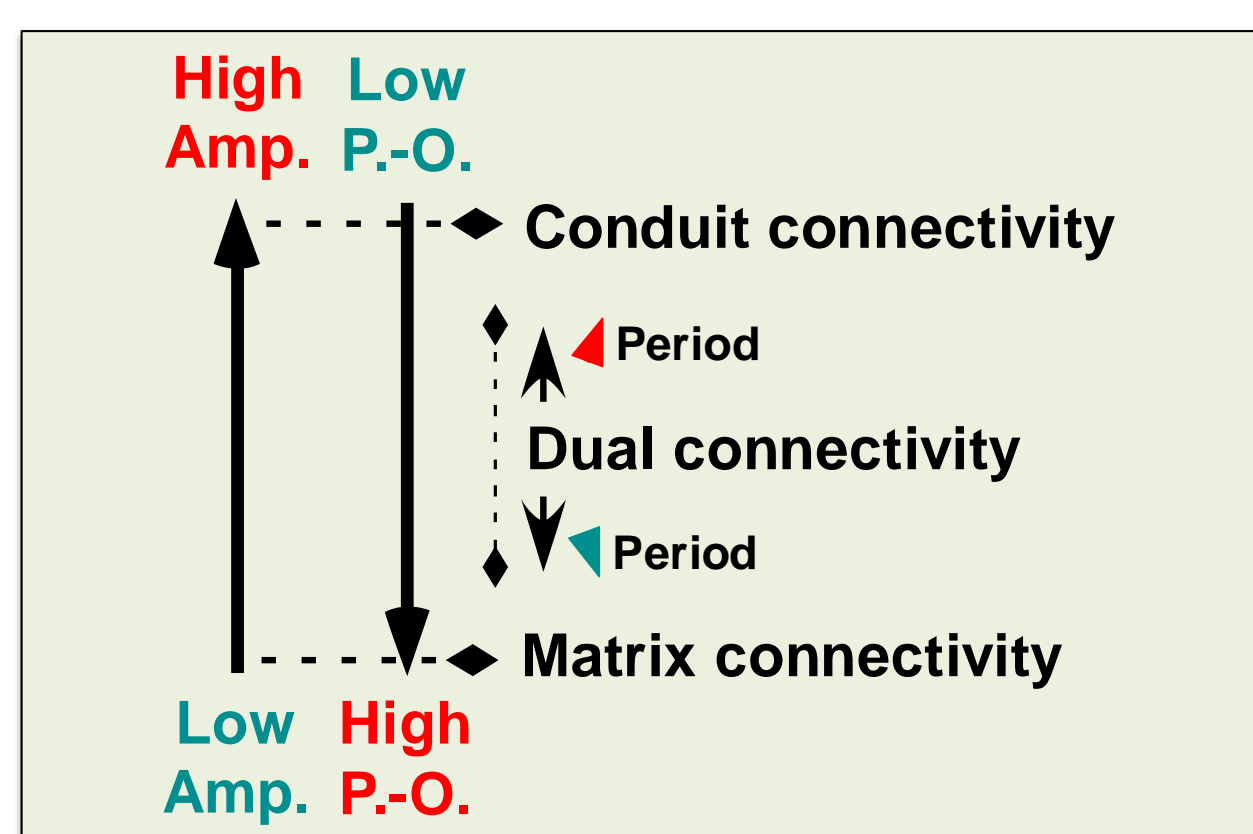


▲ (fig.3) Relative amplitude (blue) and phase offset (orange) responses for different periods (1 and 5 min).

### Impact of the period of signal on the responses

An increase of the period of signal tends to bring the 'dual' responses closer to 'conduit' responses (increases the amplitude, decreases the phase offset), while a decrease of the period generates the opposite effect and bring the 'dual' responses closer to 'matrix' responses (fig. 4). Thus, a lower period will better characterize the direct conduit connectivity while a higher period will permit to investigate farther in the less conductive media around the main conduit network.

► (fig.4) Schema showing the effect of the period on the amplitude and phase offset responses and the interpreted connectivity.

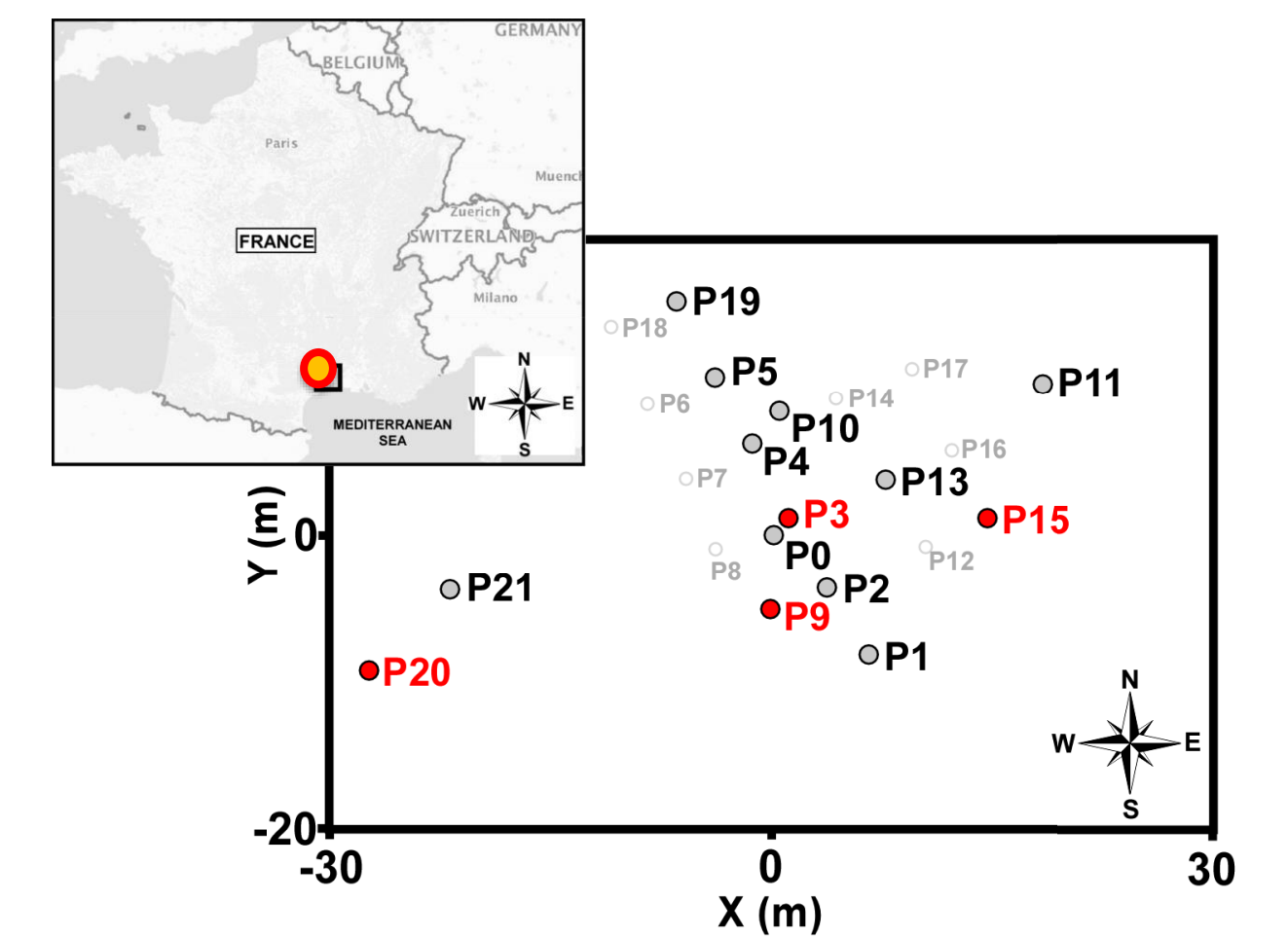


[1] Fischer, Jardani, Cardiff, Jourde, Lecoq. 2018. Hydraulic Analysis of Harmonic Pumping Tests in Frequency and Time Domains for Identifying the Conduits Networks in a Karstic Aquifer. *Journal of Hydrology* 559: 1039-1053.  
[2] Fischer, Jardani, Jourde, Cardiff, Wang, Chedeville, Lecoq. (Under review for *Advances in Water Resources*). Harmonic Pumping Tomography Applied to Image the Hydraulic Properties and Interpret the Connectivity of a Karstic and Fractured Aquifer (Lez Aquifer, France).  
[3] Fischer, Jardani, Lecoq. 2017. A cellular automata-based deterministic inversion algorithm for the characterization of linear structural heterogeneities. *Water Resources Research* 53: 2016-2034.

## APPLICATION CASE (Quantitative study) Oral presentation on Wednesday + Article under review [2]

### Study site and pumping investigation

We have led a harmonic pumping investigation in the 'Terrieu' karstic study site in France (fig.5). The pumping was performed on 4 different wells, each time with 2 different periods of signal (2 and 5 min), while measuring the amplitude and phase offset responses in 13 boreholes.



▲ (fig.5) Localization of the site and map of the boreholes used as pumping points (red) and measurement points (black and red).

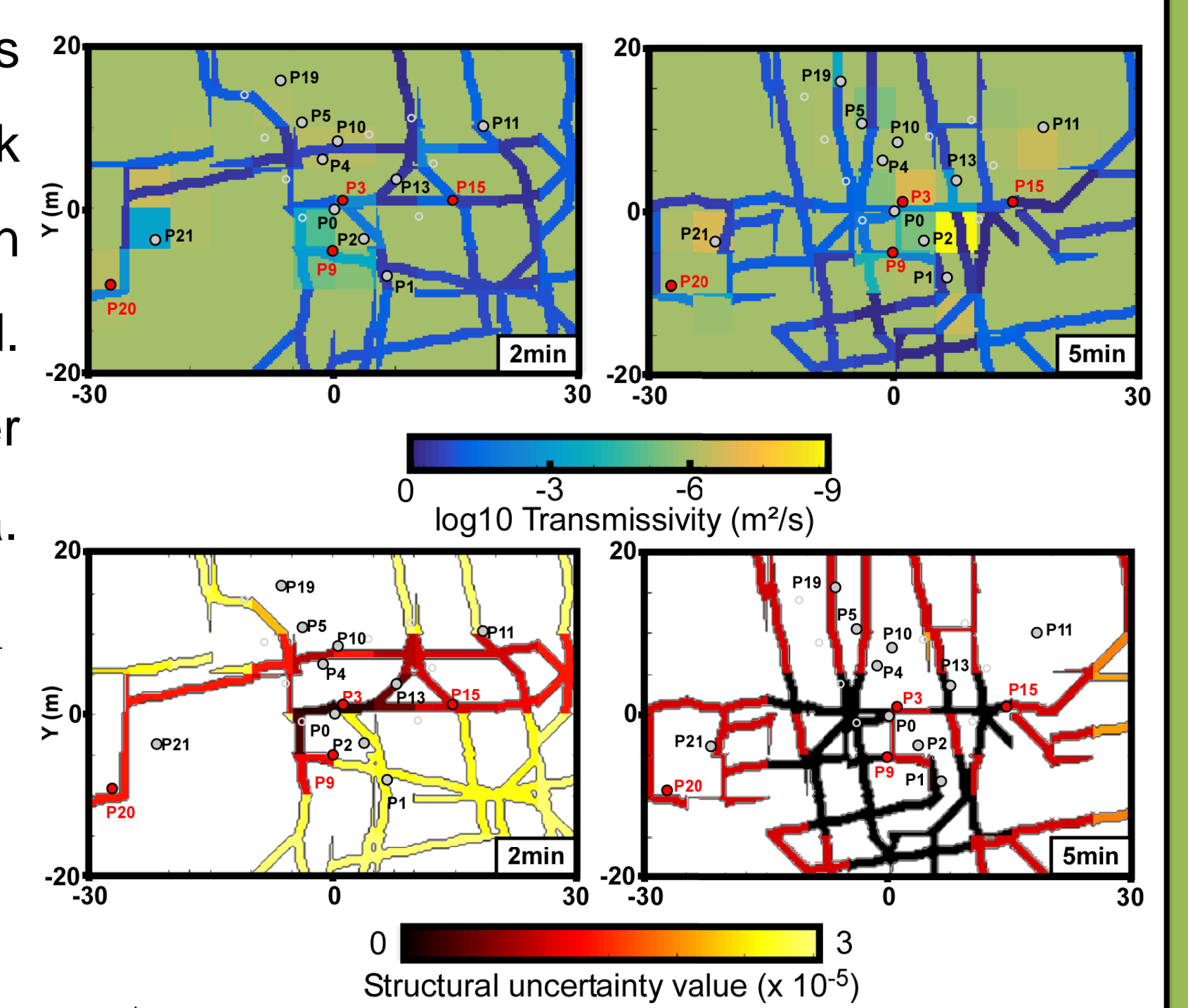
### Modeling

We created a 2D model to simulate, in a

frequency domain, the oscillatory responses on the site. We performed inversions on the property of the model, applying the CADI method [3], to reproduce with the model the amplitude and phase offset responses measured during the investigation. Different inversions were led with the responses to the 2 different periods separately, and then jointly using the separate results as new initial models.

### Results

The inverted transmissivity fields (fig. 6) present a denser network with the responses to the 5 min period than with the 2 min period. This denser network is also better constrained with these '5 min' data.



▲ (fig.6) Maps of inverted transmissivities and posterior uncertainties on the network structure for oscillatory signals of period 2 min and 5 min.

	PERIOD=2MIN			PERIOD=5MIN			
	Est.	Sep.	Joint	Joint	Sep.	Est.	
P0	○	○	○	○	○	○	P0
P1	○	○	○	○	○	○	P1
P2	○	○	○	○	○	○	P2
P3	○	○	○	○	○	○	P3
P4	○	○	○	○	○	○	P4
P5	○	○	○	○	○	○	P5
P9	○	○	○	○	○	○	P9
P10	○	○	○	○	○	○	P10
P11	○	○	○	○	○	○	P11
P13	○	○	○	○	○	○	P13
P15	○	○	○	○	○	○	P15
P19	○	○	○	○	○	○	P19
P20	○	○	○	○	○	○	P20
P21	○	○	○	○	○	○	P21

×: in a conduit = conduit connectivity response,  
⊗: close to a conduit (< 0.5 m) = conduit connectivity response,  
○: close to a conduit (< 2 m) = dual connectivity response,  
-: in the matrix = matrix connectivity response

▲ (fig.7) Hydraulic connectivity interpreted from the maps of properties inverted with the responses to the 2 min and 5 min signals separately (Sep.) and jointly (Joint).

A degree of connectivity of each borehole toward the karstic network can be easily interpreted from these property maps (fig. 7).

### Impact of the period of signal on the responses

An analysis of the different maps of properties, uncertainties and of the differences between the results of the separate and joint inversions indicates that responses to a lower period hold a better information on the connectivity to the most conductive structures, while a higher period permits to better map the flows mobilized in conduits but also in less conductive karstic structures (fig. 8).

► (fig.8) Information extracted from the responses to the harmonic pumping tests led with 2 different frequencies at the 'Terrieu' site.

**HIGHER FREQUENCY INFORMATION:**  
Borehole connectivity to the main conduits network  
● In or close to (< 50 cm) the conduits network  
○ 1 or 2 m away from the conduits network  
○ More than 2 m away from the conduits network

**LOWER FREQUENCY INFORMATION:**  
Localization of the karstic structures (conduit, fissures, fractures,...)

