Hydrogeological Experimental Site of Poitiers (France)

Afzal Chamroo * **Régis Ouvrard** * **Thierry Poinot** *
Jacques Bodin ** **Benoit Nauleau** ** **Gilles Porel** **

* *University of Poitiers, Laboratoire d'Informatique et d'Automatique pour les Systèmes (LIAS), Bât. B25, 2 rue Pierre Brousse, TSA 41105, 86073 Poitiers Cedex 9, France*
e-mail: firstname.name@univ-poitiers.fr
** *University of Poitiers, Institut de Chimie des Milieux et Matériaux de Poitiers (IC2MP), Bât. B27, 4 rue Michel Brunet, TSA 51106, 86073 Poitiers Cedex 9, France*
e-mail: firstname.name@univ-poitiers.fr

Abstract: In hydrogeology, understanding the behavior of aquifers is an important issue. May it be for forecasting the availability of water on a long term or for estimating the impact of pollutants when injected at different regions, modeling of an aquifer is very useful for hydrogeologists. This paper gives an overlook of the different types of tests on a particular site, namely the Hydrogeological Experimental Site (HES) of Poitiers (France). The aim is to show that the HES is a huge instrumented test bed allowing different types of experiments. Thus, system identification users can expect to gather large series of input-output datasets so as to experiment their own tools. Note that a large database exists concerning already-run tests, but what is interesting is that new experiments can be programmed so as to account for customized datasets. As a counterpart, the use of HES data should promote proper modeling of the underlying aquifer, thus contributing to the hydrological research field.

Keywords: Parameter estimation, Aquifer modeling, Slug test, Pumping test, Dipole test, Tracer test.

1. INTRODUCTION

Even if our planet's surface is covered with water up to 70%, availability of potable water on our overcrowded Earth is today a major issue. For sure, aquifers which can be found at various areas, represent an important source of underground water which can be pumped out and processed for domestic, agricultural and industrial purposes. However, freshwater aquifers which benefit from a limited recharge by meteoric water can be over-exploited. Moreover, in some cases, depending on local hydrogeology, non-potable water (presence of pollutants, mineral poisons, etc.) may be drawn from hydraulically connected aquifers leading to serious health problems.

Fortunately, still in 2013, Australian researchers have discovered massive aquifers underlying the coasts of Australia, China, North America and South Africa (Post et al. (2013)). With an estimation of half a million cubic kilometers of low-salinity water, those oceanic aquifers can potentially account for a large water supply for many years to come, given sustainable exploitation.

Understanding and thus modeling underground water transfers is an important issue for hydrogeologists. This modeling can for instance help in predicting future water availability and in understanding how pollutants are dispersed from one area to another through our precious liquid. For this sake, PDE-based analytical models of water flow in aquifers can be found in literature (Butler (1997), Theis (1935)). However, those models require a lot of geometrical hypotheses which are not verified in real cases.

In view of understanding and forecasting underground water flow, researchers in hydrogeology have been considering experimental data coming from aquifers equipped with several sensors and actuators (pumps). And in order to promote long-term monitoring of ground water data, several water databases have been developed (De Dreuzy et al. (2006), Seyfried et al. (2001)). For instance, the ERO (French Experimental Research Observatory) has developed the H^+ database (http://hplus.ore.fr) which is a network of hydrogeological sites (three sites in France, one in India and one in Majorca) capable of providing data (including long-term observations) relevant to the understanding of the water cycle and of the motion of solute elements in aquifers.

This paper provides an overview of the different types of tests that can be performed on a particular hydrogeological experimental site. Being in a benchmark session, its aim is not to account for any identification technique, but to show the types of input/output signals that can be used in view of modeling different phenomena in an aquifer.

2. THE HYDROGEOLOGICAL EXPERIMENTAL SITE (HES) OF POITIERS

The present paper focuses on one particular site: the Hydrological Experimental Site (HES) of Poitiers, located in the west of France, as shown on Fig. 1. Close to the campus, the HES is a field research facility operated by the University of Poitiers covering an area of 12 hectares. It is located over the north flank of a geological area called "Seuil du Poitou" or "Poitou Threshold" (Gabilly and Cariou (2007)). This area marks the transition between the Aquitaine and Paris sedimentary basins. Consisting of Jurassic carbonate rocks that lie on a Hercynian crystalline basement, the Poitou Threshold includes two stacked aquifers separated by the marly Toarcian aquitard (20 m thick):

- the Lower and Middle Lias Aquifer (5 to 10 m thick),
- the Dogger Aquifer (100 m thick).

The aquifer underneath the HES is known to be a karstic fractured limestone one showing sub-horizontal layers cut by sub-vertical fractures stemming from constraints of the Pyrenean tectonic phases (between Eocene and Pliocene epochs) (Kaczmaryk and Delay (2007)). The large-scale sub-vertical fractures are organized in a non-dense network and there are traces of karstification along these fractures and the stratification planes. At the site, the Jurassic limestone behaves as a 100 m thick confined aquifer underneath about 10 to 25 m of Tertiary clays. Preliminary studies have shown that flow mainly takes place in a few horizontal bedding planes which are hydraulically connected by sub-vertical fractures. Water storage is principally due to the porous limestone of the upper Bajocian and the Bathonian. For more information concerning the geological aspects of the HES, please refer to Audouin et al. (2008) or Chatelier (2010).

Supported by the WATER program of Poitou-Charentes region and financed by the ERO, research studies have been undertaken by hydrogeologists of the University of Poitiers, with the overall objective being the development of modeling approaches for groundwater flow and solute transport down to depths planned for drinking and/or agricultural water supply in heterogeneous carbonate aquifers. The models thus obtained can then help in protecting and managing groundwater resources. Studies on the HES focus mainly on one of the two underlying aquifers: the 100 m thick Dogger aquifer.

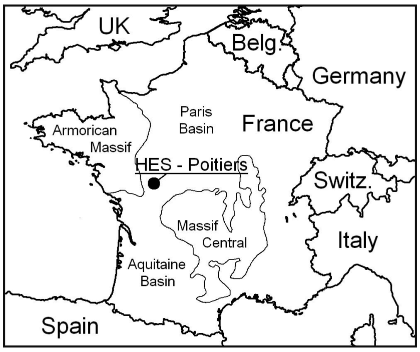

Fig. 1. Location of the Hydrogeological Experimental Site of Poitiers

Works carried out by the hydrogeologist team involved digging several wells so that by means of pumps and appropriate sensors, not only is it possible to observe how the aquifer behaves naturally, but also to enable experimental tests by using specific protocols. These works have now led to 35 instrumented boreholes on the HES, meeting depths going up to 165 m underground. Spatially distributed as nested five-spots (an elementary square pattern made of one central well and four corner wells), most of them were drilled on a regular 210 m × 210 m grid (Fig. 2). As a global system, the HES can be considered as a network of interconnected wells. The interest of this boreholes setting is that it enables characterization of the aquifer under the 12 hectares of the HES though different types of tests, some of which being described in this article.

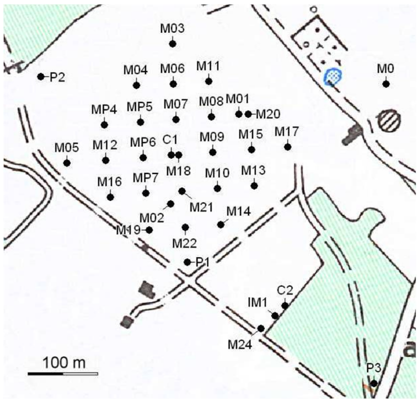

Fig. 2. Drilled boreholes on the HES cover a grid of 210 m × 210 m

3. ANALYTICAL MODELING OF AQUIFERS

As mentioned above, the wells in an aquifer are interdependent. Modeling of an aquifer should be able to account for this interdependency so that hydrogeologists can consider forecasting on hydrogeological sites. Typically, if water is pumped out at a given well, the pressure in the aquifer that feeds the pumped well declines. This decline in pressure will lead to a lowering of the water level in some neighboring observation wells. Concerning the modeling of aquifers, it is possible to rely on physical equations to describe the functioning. Nearly all methods used to describe the aquifer's behavior during a pumping test are based on the Theis solution (Theis (1935)), which is built upon the most simplifying assumptions. Other methods relax one or more of those assumptions and therefore give a more flexible (yet more complex) result.

Given an isotropic permeability, the local equation for an underground flow is (Bear (2007)) $\mathrm{div}(\mathrm{grad} h) = \frac{S}{T}\frac{\partial h}{\partial t}$, where h [$\mathbf{L}$] is the hydraulic charge (potential), S [-] the storativity coefficient, T [$\mathbf{L}^2.\mathbf{T}^{-1}$] the transmissivity and t [$\mathbf{T}$] the elapsed time. In polar coordinates, we have:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}, \qquad (1)$$

where r [$\mathbf{L}$] is the distance between the pumping well and the observation well. The assumptions made for an aquifer when using the Theis approach (Theis (1935)) are given below:

- The aquifer is supposed to be horizontal, homogeneous, isotropic, infinite and of constant thickness.
- It is supposed to be confined such that the upper layer is not subject to atmospheric pressure.
- The pumped well is supposed to penetrate completely the aquifer and its diameter is considered negligibly small.
- All pumped water is considered to come from the aquifer and to be rejected instantaneously.
- The well is to be pumped at a steady rate.
- The underground flow is supposed to be laminar.

The solution given by Theis to (1) with initial condition $h(r, 0) = 0$ and boundary condition $h(\infty, t) = 0$ is:

$$h(r,t) = \frac{Q}{4\pi T} W(u) \text{ with } u = \frac{r^2 S}{4Tt}. \qquad (2)$$

- Q $[\mathbf{L}^3.\mathbf{T}^{-1}]$ is the constant pumping rate,
- $W(u)$ is the so-called "well function" corresponding to an exponential integral which can be approximated by:

$$W(u) = -\gamma - \ln(u) + \sum_{k=1}^{\infty} \frac{(-1)^{k+1} u^k}{k k!}, \qquad (3)$$

- u [-] is the Theis variable,
- γ is the Euler-Mascheroni constant ($\approx 0,577216$).

Theoretically speaking, the Theis method requires only one piezometer to determine the hydrodynamic parameters T and S of an aquifer. However, in practice, there should be a given pair (T, S) for each piezometer installed on site, since the aquifer never match the theoretical assumptions.

4. PUMPING TESTS

In view of characterizing an aquifer, hydrogeologists often consider the so-called *pumping test*.

4.1 Principle

During this experiment, water is pumped out at a steady rate for a relatively long period of time at a well so that the response of the aquifer can be analyzed by the water level changes at *neighboring observation wells*. In fact, once water is pumped out of a well, a change of pressure is produced in surrounding wells, thus causing water level changes. The water level drop, often referred to as a *drawdown* by hydrogeologists, is measured by piezometers placed at each well of a site. This pumping test helps in analyzing such characteristics of an aquifer as its conductivity, its storativity and its transmissivity. It is to be underlined that the pumped water is evacuated far away enough from the surrounding observation wells so that the reintroduction effect can be considered as negligible on the measured drawdowns.

4.2 Experimentation on the HES

In this section, some curves are given to illustrate a pumping test which has been carried out recently and whose results have allowed black-box modeling of the interdependency between pairs of wells (Chamroo et al. (2014)). During this experiment, water was pumped out of well M06.

Excitation signal Fig. 3 illustrates a pumping process carried out at well M06, $q(t)$ being the chosen shape for the flow rate. Aside the step and ramp type excitation shape, a change of the level was included in the last part of the experiment for non-linearity test sake.

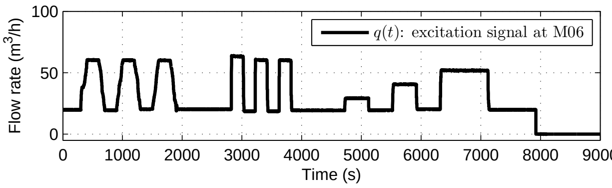

Fig. 3. Flow rate for water extraction at M06

Wells responses This pumping excitation implied a local water-level change in the well M06 and consequently, neighboring wells responded to this stimulation. Fig. 4 gives an overview of the wells responses.

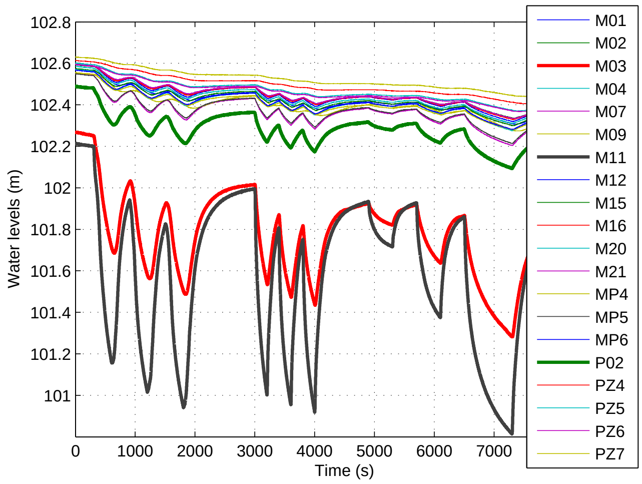

Fig. 4. Experimental output data at different observation wells

Input-output dataset In view of reproducing the behavior of the drawdown of an observation well to that of well M06 where water was pumped out, the model for any observation well Mxx to be identified shows:

- an input signal $u(t)$ which is the drawdown at M06,
- an output signal $y(t)$ which is the corresponding drawdown at the given observation well Mxx.

Fig. 5 gives an example of an input-output dataset when considering the dependence of well M04 on M06.

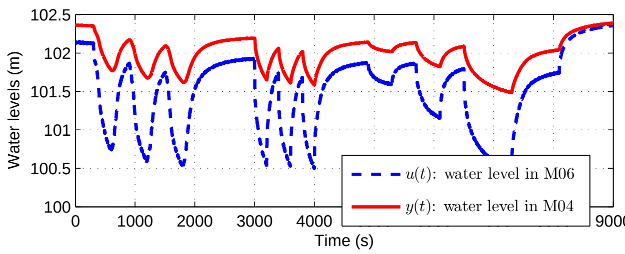

Fig. 5. Example of an input-output dataset

5. DIPOLE TESTS

In the previous section, the study focused only on the *removal* of water at a well. Another experiment known as the dipole test can be considered on to analyze aquifers.

5.1 Principle

In this case, two wells (say W_1 and W_2) are chosen to define the dipole. Then, as before, water is pumped out of W_1. But instead of being evacuated far away, the removed water is reintroduced in W_2, whatever the pumping flow signal shape is. Then, the drawdown is observed in other surrounding wells.

5.2 Experimentation on the HES

In this section, the M06-M22 dipole test is considered, meaning that water pumped out from well M06 is reintroduced in well M22. Knowing that the flow rate signal for the pumping out of water from M06 was a step signal, Fig. 6 shows the drawdowns at surrounding wells - note that on this semi-log plot, the vertical scale does not show the absolute levels as the previous plots, but only their variations from the initial values. Depending on the connectivity of any observation well Mxx to M06 and M22, the corresponding drawdown can be either positive or negative at steady state. Typically, the drawdown of a well close to M06 should be rising and on the other hand that of one close to M22 should be falling. Intermediate wells should see their water level fairly affected. However, the notion of "closeness" might not be necessarily geographical. It depends on the type of internal connections inside the aquifer.

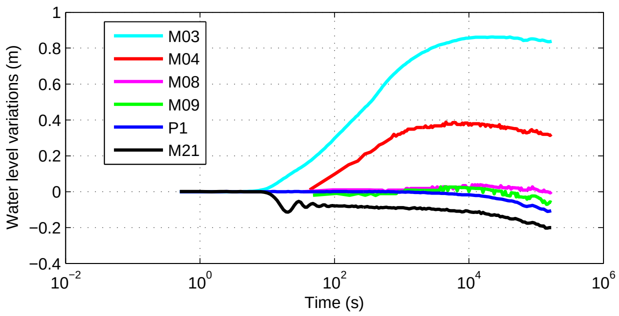

Fig. 6. M06-M22 dipole test: water level variations at 6 observation wells

According to hydrogeologists, it should be possible to predict drawdowns in any observation well. Indeed, if the transfer functions Mxx/M06 and Mxx/M22 have been modeled independently, the combining effect of a dipole test should be predictable simply by superposition. The challenge is to be able to forecast the different curves of Fig. 6, knowing that a comparison of modeling approaches can be found for the dipole test on the HES in Bodin et al. (2012).

6. SLUG TESTS

As opposed to the long lasting pumping tests, hydrogeologists can also consider *slug tests* on aquifers in order to rapidly get an estimate of it's parameters without necessarily requiring pumping. Slug tests help in determining near-well aquifer characteristics and are often used to estimate the transmissivity (hydraulic conductivity) of the medium.

6.1 Principle

Typically, this kind of experiment involves adding or removing a given volume of water as quickly as possible at a given well so as to create a disturbance in the water level. This excitation operation being very brief (a few seconds), the resulting consequence, which is a change in water level at the same well, can be considered as an *impulse response*. Thus, the goal is to monitor the evolution of the water level over a period of time which, by the way, is usually shorter than for pumping tests.

Note that since the flow rate into or out of the well is not constant in the case of slug tests, the standard Theis solution is not applicable. Mathematically, the Theis equation is the solution of the groundwater flow equation for a step increase in discharge rate at the pumping well. A slug test is instead an instantaneous pulse at the pumping well. Hence, a superposition of an infinite number of sequential slug tests through time would effectively be a standard Theis aquifer test - this can be viewed as a convolution.

6.2 Experimentation on the HES

In order to visualize the effect of a slug test on the HES, Fig. 7 illustrates the behavior at well M03 for different slug tests - again, the vertical scale does not show the absolute water levels but only their variations from the initial values. During the slug test, water was introduced in M03 for a short time Δt. The resulting water level variation at M03 itself was monitored for different values of Δt.

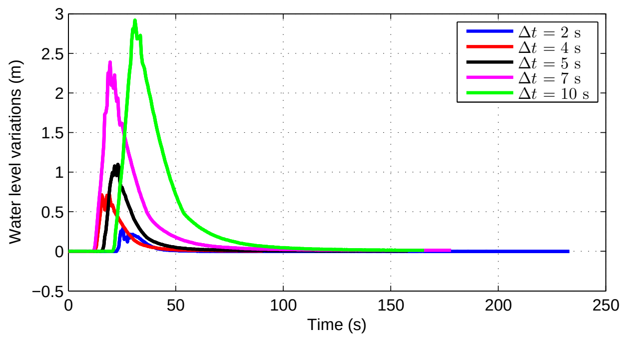

Fig. 7. Slug tests on well M03

Depending on the properties of the aquifer and the size of the slug (amount of water added or removed), the water level may return to pre-test levels very quickly. Moreover, in some cases, the responses may show oscillations on a short term. This is due to inertial effects linked to the well. It is to be noted also that if the slug is not big enough, the resulting signals of the slug test can be blurred with noise. Typically, wells of large diameters require a larger amount of water extraction/introduction.

7. TRACER TESTS

All those tests mentioned so far imply a transfer of pressure from one point to another of the aquifer. An interesting experiment, useful for the study of pollutant displacement, is the analysis of mass transfer.

7.1 Principle

In order to carry out the tracer test, hydrogeologists introduce a small amount of a harmless chemical tracer in a given well (impulse excitation). Typically, fluorescent substances with molecules close in size to that of water are used as tracers. The tracers are meant to move along flow pathways in the aquifer. Thus, the goal is to detect and measure the concentration of the tracers at any surrounding observation well so as to be able to plot the evolution of this concentration in time. Technically, to be able to measure the instantaneous concentration, the observation well should be equipped with a flow-through fluorometer calibrated beforehand with standards of known concentration values. It is to be highlighted that though the excitation is induced for some seconds, the measurement can sometimes require several weeks so as to catch all the phenomena of mass transfer. Note that if the flow of the tracer was left naturally, observation time would have been even longer and the substance would have taken several routes, thus spreading around. This is why hydrogeologists inject a small volume of a tracer at any well W_1 and pump out water at a constant rate at any observation well W_2 so as to favor a pathway between W_1 and W_2, since that a pressure change is induced. Hence, characteristics of the aquifer for mass transfer between W_1 and W_2 can be explored. When extrapolated to any pair W_i, W_j, hydrologists can expect to better understand the flow process in an aquifer.

7.2 Experimentation on the HES

Tracer tests have recently been undertaken on the HES. After several experiments, hydrogeologists of the university of Poitiers have developed useful techniques to carry out efficiently this type of test. First, in order to optimize the long-lasting and costly experiments, a combination of fluorescent tracers can be injected at one shot instead of separately introducing them during different experiments. Note that one of the the aims of hydrogeologists is to try out different tracers (uranine and sulforhodamine among others) to better understand the transport mechanism. Secondly, the injection procedure, which is a delicate one, has been sharpened throughout the different experimentations. As a matter of fact, pouring the tracer as a liquid at the top of a well can be inefficient for the transfer to other wells. It has been noticed that due to the physical structure of the aquifer, conductivity will occur mainly at a given depth. With the use of video cameras, hydrogeologists have learned to use a closed tube of small diameter with lateral holes at specific depths (depending on which observation well is being tackled) so that a very few amount of the tracer is necessary to enable an efficient injection into the aquifer. Once the liquid is poured, some water is also poured so as to rinse [1] the tube and ensure propagation of the totality of the tracer's molecules.

[1] This process is called "flushing"

Fig. 8 shows the type of signal obtained for a tracer test induced at well M07. The fluorescent tracer, uranine (volume: 5 L, concentration: 8 g/L) was injected at M07 and its transfer was tracked at M06 (50 m away) where a constant flow rate of 50 m^3 per hour was applied to enable a favored pathway between wells M07 and M06. Measurement of the fluorescent tracer by a fluorometer then allowed an estimation of the concentration of the tracer. Note that the injection process can be considered to instantaneous, thus corresponding to an impulse and that the measurement at M06 lasted nearly one whole day with a sampling time-step of one minute.

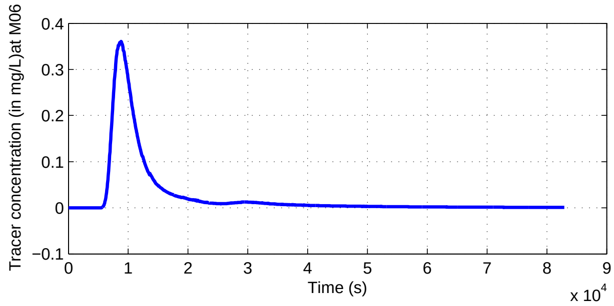

Fig. 8. Concentration estimation of a marker at M06 when injected at M07 (50 m away)

Fig. 9 shows another experiment of the tracer test which lasted more than 60 hours. In this case, uranine (volume: 5 L, concentration 2.4 g/L) was injected in well M04 at a depth of 76 m and as water was pumped at a constant rate in M06, the corresponding concentration was measured at that observation well. The shape of the signal is quite similar to the previous case, thus showing the characteristic transfer of mass from one point to another of the aquifer. However, the present case shows a second peak which is much more pronounced than formerly. This phenomenon is explained by the fact that the incoming of the tracer at the observation point is not only due to one main pathway, but also to a secondary one. There might be other routes taken by the substance, but the volume in those routes is surely negligible in this case.

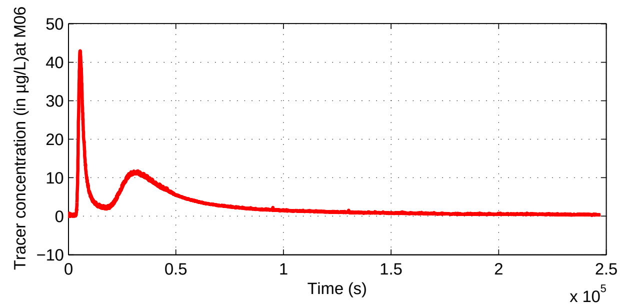

Fig. 9. Concentration estimation of a marker at M06 when injected at M04 (50 m away)

8. CONCLUSION AND OUTLOOK

The HES represents a powerful realistic test bed in the hydrogeological field. Not only does it enable hydrogeologists to understand and predict underground water flow in an aquifer, but also allows application of several tools in other fields, like system identification for example. As mentioned previously, the HES of Poitiers being part of a network of hydrogeological sites, several datasets can be accessed on an open database of the ERO (French Experimental Research Observatory) at http://hplus.ore.fr/base-de-donnees-fr. On top of that, if required, specific protocols can be considered in partnership with the hydrogeologist team for future experiments. Nevertheless, it should be kept in mind that any use of data and/or collaboration with the team of Poitiers must contribute in promoting better modeling of the aquifer offering means to analyze its behavior through meaningful parameters eventually leading to the transmissivity and storativity in which hydrogeologists are particularly interested. The challenge of the study is the fact that those parameters are not constant throughout the site since the underlying aquifer is known to be heterogeneous. As a matter of fact, the pumping tests carried out on the HES helped in concluding that the amplitude of water-level changes is not strictly proportional[2] to the distance of the observation well from the excited one (Bernard (2005)). It is believed that there exists a heterogeneity of the water flow linked to the fractured nature of the aquifer. Fig. 10 gives an example of the kind of result which could be helpful to hydrogeologists. On this figure, we can easily evaluate the interdependency of different pairs of wells. Note that this result, obtained some years ago, might no longer hold today due to the constant evolution of the aquifer which is partly due to manipulations on the site. This is why it is interesting to be able to contribute in methods enabling the observation of parameters of the aquifer on a long-term basis.

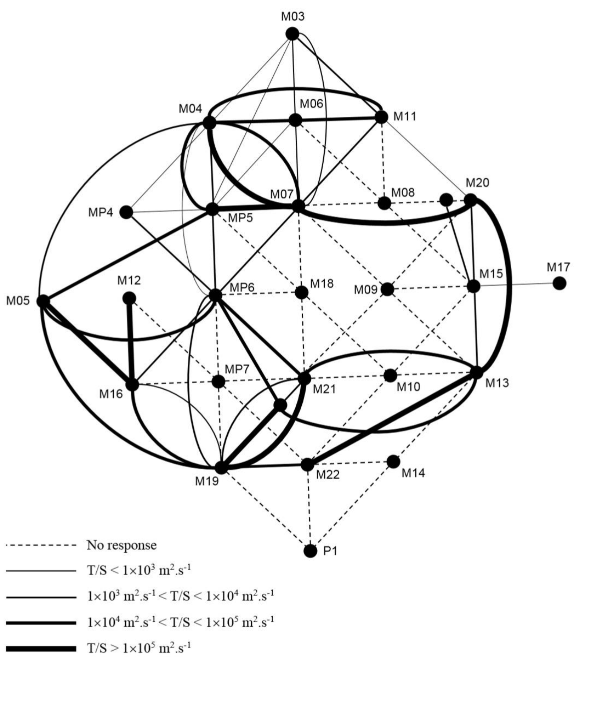

Fig. 10. Hydraulic diffusivity (T/S) values interpreted from cross-borehole slug-tests with the method of Audouin and Bodin (2008)

[2] Theoretical studies assume that water-level variation decreases in magnitude with radial distance from the pumping well.

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