Continuous-Time Model Identification of Wells Interaction on the Hydrogeological Experimental Site of Poitiers

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***Abstract*— In hydrogeology, estimating aquifer permeability is an important issue. This can be useful in understanding the flow of pollutants from one area of an aquifer to another. For this aquifer analysis sake, the Hydrogeological Experimental Site of Poitiers (France) covering a limestone aquifer is an appropriate instrumented test bed enabling measurement of hydraulic responses of a series of observation wells due to a step-type pumping out excitation at a given well. Given the input-output data, black-box continous-time modeling is quite a straight forward process as shown in this paper. The aim is then to be able to use the identified parameters to classify the different wells according to how sensitive they are to the one having been excited. A correlation between black-box parameters and hydrogeological ones is then established.**

I. Introduction

Most land areas on Earth have some form of aquifer underlying them. This is an underground layer of water-bearing permeable rock or unconsolidated materials from which groundwater can be extracted using a water well. Very often representing a source of potable water for human consumption and agriculture, fresh-water aquifers which benefit from a limited recharge by meteoric water can be over-exploited. 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.

Understanding underground water transfers in different media is an important issue in hydrogeology. This can lead, for instance, to the prediction of future water availability and to know how pollutants are dispersed from one area to another. However, modeling groundwater flow and solute transport in fractured (karstified) limestone aquifers is quite troublesome, specially because of the different types and degrees of heterogeneity of the prevailing limestone. As a matter of fact, those type of aquifers are highly heterogeneous due to the presence of low-resistance pathways which are sometimes enlarged by dissolution and which allow faster propagation than the actual intergranular permeability of the rock matrix [17].

In view of “evaluating” an aquifer, hydrogeologists often conduct the so-called *pumping test* or *aquifer test* whereby water is pumped out at a steady rate for a long period of time at a well so that the response of the aquifer can be analyzed by the water-level changes in the observation wells (several piezometers can be used). *Slug tests* can also be used to get a quick estimate of the aquifer properties by applying an instantaneous change and analyzing the effects in the same well. However, slug tests are mostly used to study the behavior of a single well, whereas the pumping test helps in analyzing the characteristics of the aquifer, such as hydraulic conductivity, storativity and transmissivity.

Analytical models are available in literature to represent underground water flow in aquifers [4], [8]. However, those models, which are based on the geometric parameters of the aquifers require a lot of hypotheses which are often not verified in real cases. Thus, they often do not account for local phenomena in any given aquifer. Moreover, based on partial differential equations, those white-box type models are quite cumbersome to handle when it comes to numerical simulation.

In order to understand and to forecast underground water flow, researchers in hydrogeology have been considering experimental data coming from aquifers equipped with several sensors. In this article, we are going to consider a known site in France, namely the Hydrogeological Experimental Site (HES) of Poitiers which is well located for water flow analysis. As from 2002, 35 wells have been dug to meet depths going up to 160 m so that by means of different sensors it is possible to observe the interconnection between the wells and thus understand underground water flow at a realistic scale. This huge experimental test bed is an opportunity to fetch data either during natural long term evolution of the aquifer or by means of typical excitation of pumps set up at the wells. To do so, different variables such as the levels of ground water at each well can be measured in real time.

In this paper, we are going to briefly describe the HES of Poitiers and give some main features of common analytical modeling of an aquifer. Then, the main issue is to use experimental data after a pumping test in a given well in view of modeling the dependence of neighboring wells. In this case, we consider level data at different wells as an output of a system whose input is the level at the pumped well. Hence, by means of an output-error continuous-time identification algorithm, it is possible to propose a parsimonious black-box linear model fitting to the best the behavior of a pair of wells. Moreover, through an appropriate structure of the model, some black-box parameters can give a clue to physical behaviors. It is thus possible to propose different classes of interdependencies according to simple parameters like the gain and time constants. A comparison is done using the analysis undertaken by hydrogeologists. In this way, the

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study shows a form of correlation between the black-box model and the analytical one, given a proper interpretation of the parameters.

II. The Hydrogeological Experimental Site (HES) of Poitiers

In hydrogeology, there is a real need to develop and maintain databases that gather data collected at different specific geographical sites. This is necessary to promote long-term monitoring of ground water data. Thus, as from late 1980's, several ground water databases have been developed (e.g. [6], [14]). For this sake, the ERO (French Environmental Research Observatory) has developed the H^+ database (http://hplus.ore.fr) which is a network of hydrogeological sites (Ploemeur, Poitiers, Majorca, Le Durzon (Larzac), LSBB, Hyderabad (India)) 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. The ERO thus naturally encouraged investigations on the well located site of Poitiers. Investigations were ignited in 2002 through the Hydrasa team (IC2MP, University of Poitiers) via a project supported by the WATER program of the region of Poitou-Charentes and financed by the ERO. The overall research objective related to this site is to improve the understanding of flow and solute transport in calcareous aquifers, down to depths planned for drinking and/or agricultural water supply. Close to the campus of the University of Poitiers, the HES of Poitiers covers an area of 12 hectares. From a geologic point of view, it occupies the north flank of the "Seuil du Poitou", a huge Mesozoic carbonate plateau marking the transition between the Aquitaine and Paris sedimentary basins. The Jurassic limestones, which overlie a Hercynian crystalline basement, include two stacked aquifers:

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

These two aquifers are separated by the marly Toarcian aquitard (20 m thick). Note that the studies conducted at the HES focus mainly on the Dogger Aquifer.

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) [7]. It is believed that the large-scale sub-vertical fractures are organized in a non-dense network and that 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 [1] or [5].

Works carried out by Hydrasa involved digging several wells so that by means of pumps and appropriate sensors, not only is it possible to observe how the aquifer acts naturally, but also to enable experimental tests by using specific protocols. These works have now lead to 35 instrumented boreholes on the HES, including 2 vertical and 2 inclined cored holes, meeting depths going up to 165 m. 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 $\times$ 210 m grid (Fig. 1). As a global system, the HES can be considered as a network of interconnected wells.

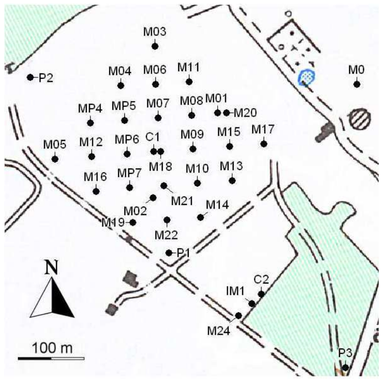

Fig. 1. Drilled boreholes on the SEH cover a 210 m $\times$ 210 m grid

In view of studying and modeling ground water flow in the underlying karstified limestone aquifer, the installed devices enable several data acquisition depending on what parameters the study wants to focus on. For instance, it is possible to pump water out of one given well at any specified flow rate and measure the change in water levels in that same well and in any other surrounding ones. By the way, this type of experiment can be used to express the interdependency of any pair of wells and this is what is considered in this present article. It is to be noted that a first series of experiment brought hydrogeologists to conclude that the amplitude of water-level changes is not strictly proportional[1] to the distance of the observation well from the excited one [3]. It is believed that there exists a heterogeneity of the water flow linked to the fractured nature of the aquifer. Meanwhile, hydrogeologists of Hydrasa have already proposed analytical models (see section III) to explain and represent the behavior of this portion of the aquifer under the HES.

III. Analytical modeling of aquifers

During the aquifer (or pumping) test 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 an observation well. 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 [15], which is built upon the most simplifying assumptions. Other methods relax one or more of those

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

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

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

where r [**L**] is the distance between the pumping well and the observation well. The assumptions made for an aquifer when using the Theis approach [15] 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:

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

- 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:

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

- 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.

IV. Black-box modeling

A. The approach

In order to get behavioral models of processes, very often automaticians make use of the black-box modeling approach, requiring simply an input-output dataset provided by a significant test (whereby the dynamics of a process is excited properly). According to the experimental output to a given excitation, experimented modelers can conveniently define the black-box model structure meant to suit the behavior of the process. Once the structure is settled in a given representation (may it be transfer function or state-space representation, in continuous or discrete time), system identification algorithms can be run to determine the model's parameters that fit to the best the model's output to that of the process, given an appropriate criterion. In this approach, physical equations of the process are simply ignored and consequently, the parameters that characterize the model do not necessarily have a physical meaning. For a complete guide on process modeling, the reader can refer to [10].

In our case, in view of proposing black-box models for the interdependence of wells, a continuous-time (CT) transfer function representation is considered. CT representation has been used specially because of the presence of two time constants (as mentioned further in this section, the process shows two dynamics, one being sometimes more than twenty times slower than the other) and the will to compare the model's parameters with the physical ones. The off-line CT-identification procedure used is an output-error one based on the well-known Levenberg-Marquardt algorithm [16].

From measured sampled data $\{u(kt_s), y^*(kt_s)\}_{k=1,\ldots,N}$ where t_s is the sampling time, the goal is to minimize the error between the measured output $y^*(t)$ and the simulated model output $\hat{y}(t)$ by modifying the parameter vector $\hat{\theta}$. Usually, the following quadratic error criterion is considered:

$$J(\hat{\theta}) = \sum_{k=1}^{N}(y^*(kt_s) - \hat{y}(kt_s, \hat{\theta}))^2. \tag{4}$$

$J(\hat{\theta})$ is minimized by an iterative procedure. In this paper, the Levenberg-Marquardt algorithm [11] is used:

$$\hat{\theta}_{i+1} = \hat{\theta}_i - \left(\left[J''_\theta + \mu I\right]^{-1} J'_\theta\right)_{\theta=\hat{\theta}_i} \tag{5}$$

where J'_θ is the gradient of $J(\hat{\theta})$ and J''_θ the Hessian, *i.e.* the first and second order derivatives of $J(\hat{\theta})$, respectively. The Hessian is obtained from the Gauss-Newton approximation:

$$J'_\theta = \frac{\partial J}{\partial \hat{\theta}} = -2\sum_{k=1}^{N}\sigma(kt_s, \hat{\theta})(y^*(kt_s) - \hat{y}(kt_s, \hat{\theta})),$$

$$J''_\theta = \frac{\partial^2 J}{\partial \hat{\theta}^2} \approx 2\sum_{k=1}^{N}\sigma(kt_s, \hat{\theta})\sigma^T(kt_s, \hat{\theta}).$$

$\sigma(t, \hat{\theta}) = \frac{\partial \hat{y}(t)}{\partial \hat{\theta}}$ is the so-called sensitivity function vector with respect to the parameter $\hat{\theta}$ and its Laplace transform $\varsigma(s, \hat{\theta})$ is defined as $\varsigma(s, \hat{\theta}) = \frac{\partial \hat{Y}(s)}{\partial \hat{\theta}}$.

Before running the algorithm, μ is initialized to a high value in order to ensure the stability of the algorithm. If the criterion $J(\hat{\theta})$ increases, *i.e.* the optimization algorithm diverges, then μ must be increased until $J(\hat{\theta})$ decreases. If $J(\hat{\theta})$ decreases, *i.e.* the search direction is good, then μ can be decreased for a faster convergence.

The output-error method is characterized, under certain hypotheses, by its unbiased asymptotic convergence [9]. However, this approach is only locally convergent, and the convergence to the global optimum cannot be guaranteed. A means of achieving global convergence is to use a suitable initialization of the output-error method, which can bring the identification process close to the global optimum. In this way, an equation error method based on the reinitialized partial moment is sometimes used to initialize the Levenberg-Marquardt algorithm [12], [13].

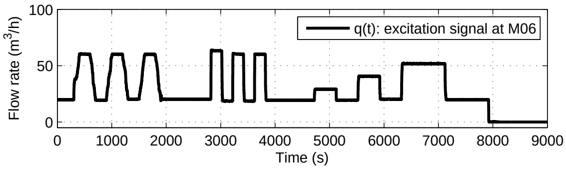

Fig. 2. Flow rate for water extraction at M06

B. Defining the model structure

The aim of the study is to model the dynamics of different wells following a change of level at one given well (M06). Thus, water has been pumped out of M06 - see Fig. 2 to view how the flow rate $q(t)$ was set. Special attention has been paid to the choice of the sampling time in order to properly account for the faster (of the two) dynamics of the aquifer. Moreover, 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. This pumping excitation implied a local water-level change in the well M06 and consequently, neighboring wells responded to this stimulation. The goal of system identification here is to model the link between the level of each neighboring well to that of M06. Hence, the input $u(t)$ of the model is the water level of M06 and its output $y(t)$ is the corresponding water level of any observation well. Fig. 3 gives an example of an input-output dataset when considering the dependence of well M04 on M06.

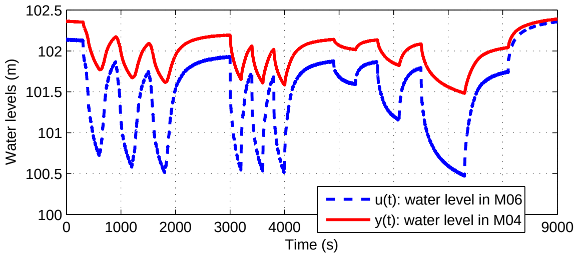

Fig. 3. Example of an input-output dataset

Analysis of the hydraulic responses of each observation well showed that most of the neighboring observation wells react with the same type of dynamics when pumping is carried out at well M06 (see Fig. 4). This similarity in their behavior is confirmed by hydrogeologists who consider that underground water flow obeys quite the same rule at different parts of the site, except that the magnitudes and reaction times might differ. Note that even if a few of them showed relatively poor sensitivity (due to a lack of connectivity according to hydrogeologists), the model of still the same structure proved to represent their (weak) dynamics. Thus, we assumed that a unique model structure can be used at each observation well.

Given the experimental protocol used for pumping (Fig. 2), the system identification procedure was run for each well during distinct phases linked to the step/ramp-type excitation. This was meant to find out whether a well behaves the

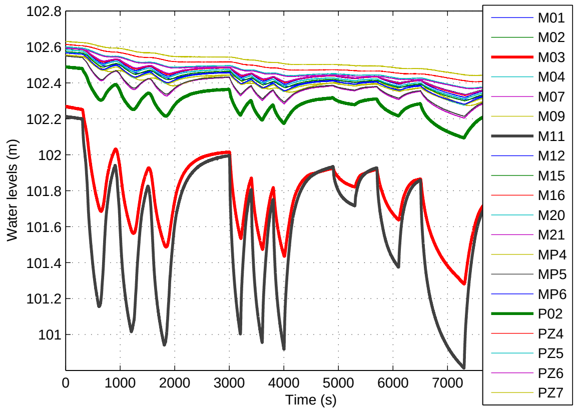

Fig. 4. Experimental output data at different observation wells

same way on rising and falling phases and to check if there is a significant non-linearity inherent to the process. The conclusion of this first analysis is that, for a given well, the same first order linear model $H_f(s) = \frac{G_f}{1+\tau_f s}$ can be used for any phase, $H_f(s)$ thus representing the immediate ("fast") dynamics of a well.

However, when this model $H_f(s)$ is run for the whole duration of the experiment (9000 s), it can be seen on Fig. 5 that the simulation does not properly represent the actual long-term behavior of the observation well. Fig. 5 clearly

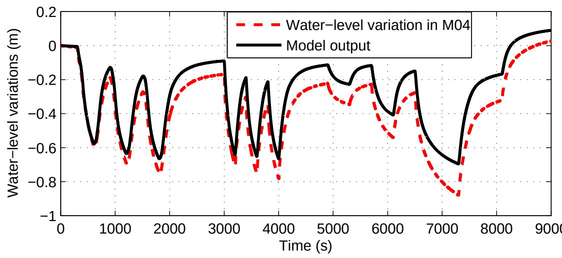

Fig. 5. Long-term run of the locally identified 1st order model

shows that although the observation well's behavior (M04 in this example) to a given excitation can be modeled by a first order transfer function, there exists a slow drift on the long term. This means that the proposed model should include a second, much longer, time constant τ_d to account for the long-term drift. However, if a canonical second order transfer function with two real poles and no zeros is used (of the form $\frac{G}{(1+\tau_f s)(1+\tau_d s)}$), the main drawback is the fact that the step response will have a nil initial gradient which does not really fit with the physical behavior. A more appropriate model in this case is:

$$H(s) = \frac{G(1+\tau_z s)}{(1+\tau_f s)(1+\tau_d s)}. \qquad (6)$$

Using the model structure given in (6) for every observation well, each one of them can be characterized by a static gain G, a "fast" time constant τ_f to describe the well's reactivity and a much slower one τ_d accounting for the drift.

It can be noticed that even if the model is a black-box one, its parameters can be used to somehow relate physical behaviors. This analysis is detailed in the following section.

C. Identification of the model's parameters

Note that since only the variations are to be modeled, the offsets of the experimental output data of each well are removed, thus bringing them to zero on the y-axis. Concerning the identification procedure, the parameter vector for each observation well is given by $\hat{\theta} = [G, \tau_z, \tau_f, \tau_d]$ and the sensitivity functions are computed as follows:

$$\varsigma_G = \frac{1+\tau_z s}{(1+\tau_f s)(1+\tau_d s)} U(s) \quad \Big| \quad \varsigma_{\tau_f} = \frac{-s}{1+\tau_f s} \hat{Y}(s)$$
$$\varsigma_{\tau_z} = \frac{Gs}{(1+\tau_f s)(1+\tau_d s)} U(s) \quad \Big| \quad \varsigma_{\tau_d} = \frac{-s}{1+\tau_d s} \hat{Y}(s)$$

The identification procedure was carried out for different wells located at different distances from the excited one. Fig. 6 shows the modeling result obtained for well M04. It can be noticed that as opposed to the curve on Fig. 5, the long-term drift is now modeled.

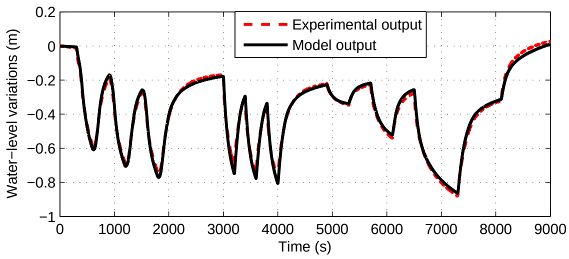

Fig. 6. Modeling result on well M04

V. Dependency classification of wells

In this section, we will gather the identified parameters of the black-box model for the whole set of observation wells in view of classifying them according to their dependency upon the excited well M06. Knowing that the aim is to be able to compare this classification with the studies carried out by hydrogeologists, analytical parameters will be used to show any correlation between the black-box model and analytical ones.

TABLE I
Wells parameters

Well	r	G	τ_z	τ_f	τ_d	T	S
M01	100	0.37	781	213	4616	9.3E-03	5.3E-04
M02	167	0.37	657	132	4766	1.8E-02	1.6E-04
M03	55	0.79	1297	57	2395	3.6E-03	1.1E-04
M04	51	0.61	1308	28	1877	5.2E-03	7.1E-05
M05	183	0.38	696	104	4654	1.8E-02	9.8E-05
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Table I shows several parameters for each observation well: the distance r in m from M06, the four identified parameters of the black-box model (see previous section) and two physical parameters (estimated by hydrogeologists for some of the wells) which are the transmissivity T given in m^2/s and the dimensionless storativity S.

A. Considering only the black-box model parameters

It is interesting to note that when we consider the hydraulic responses of different observation wells on the same axes as in Fig. 4 (not all the responses have been plotted), it is visually possible to roughly classify the wells according to their reactivity and sensitivity. The idea is to use the proposed model's parameters to enable a more reliable classification. Even if the model used is a black-box one, the structure used is simple enough to express:

1) the reactivity of each observation well by considering the (fast) time constant τ_f,
2) the degree of sensitivity by considering the gain G.

If we sort the wells according to G, it can be said that wells M14, M18, M23 and P01 are poorly sensitive. This is confirmed by the graphical responses and known by the Hydrasa team. The highly sensitive ones are M03, M04 and M11. On top of that, those 3 wells are the most reactive ones regarding the values of τ_f. In between these far end categories, we can form two distinct groups of wells having roughly the same dynamics:

- Wells M02, M05, M12, M15, M16, M17, M18, M19, M20, M21, M22, MP4 and MP6 show a gain G and a (fast) time constant τ_f of the same order , with G ranging from 0.37 to 0.38 and τ_f from 104 s to 161 s.
- Wells M07, MP5 and P02 with G ranging from 0.39 to 0.40 and τ_f from 62 s to 85 s.

These categories are quite easily recognizable graphically from the hydraulic responses for the same experiment. Note that when considering sorting according to the slow time constant τ_d linked to the drift, we obtain quite the same discrimination as with the gain G. According to hydrogeologists, the long-term drift is thought to be linked to the lateral heterogeneity of the site. In fact, in a short term, the pressure changes inferred by pumping are propagated in the HES zone (more or less radially from the pumped well). Then, after some time, the propagation reaches the outer limits of the HES where the hydrodynamic properties differ from the HES zone. This lateral heterogeneity is the consequence of the changes inferred by the installation of wells and the several pumping tests realized over the passed ten years.

Knowing the distance r of each observation well from M06, we have represented on Fig. 7 the parameters G, τ_f and τ_d with respect to r. On this figure, we can notice that those three parameters do not vary a lot according to distance r, except for some particular wells. As a matter of fact, wells M11, M03 and M04 show relatively high gains. As said before, those three close wells are highly sensitive. Their high reactivity can be seen by their lower parameter τ_f. Although well M10 shows a high gain, it is known to be poorly reactive. This is confirmed by its very high parameter τ_f, which hasn't been included on the curve to avoid squeezing the other points on the bottom part. Concerning the distant wells M14, P01 and M23, hydrogeologists are aware of the fact that they are not well connected hydraulically to M06.

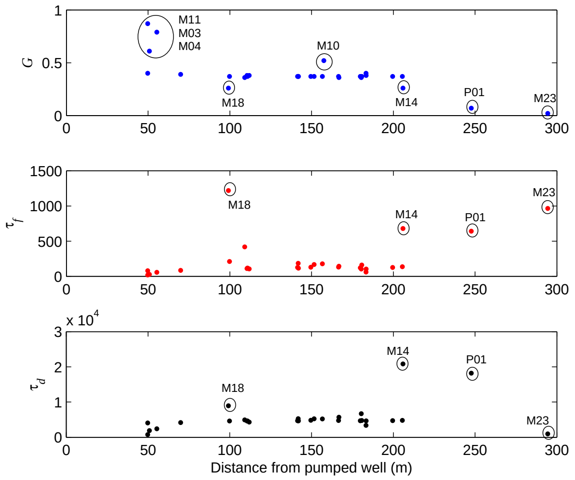

Fig. 7. Model parameters G, τ_f and τ_d vs. distance r from M06

B. Comparison with the hydrogeological parameters

According to hydrogeologists, the transmissivity to storativity ratio (T/S) can be regarded as the propagation velocity of pressure perturbations in the aquifer. Hence, it can be meaningful to compare it to the ratio r^2/τ_f as on Fig. 8 if we consider the interpretation of a diffusion process. On this plot, a significant correlation between black-box and hydrogeological parameters can be observed.

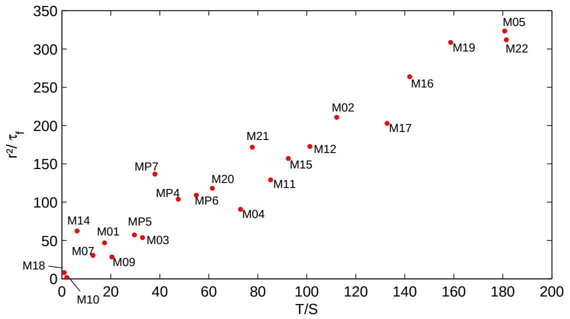

Fig. 8. Correlation between black-box and hydro. parameters

As mentioned previously, even if theoretical studies consider that water-level variation decreases with radial distance, the HES shows particular features linked to its heterogeneous nature. This is probably why the curves on Fig. 8 do not show a perfect linearity.

VI. 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 in our case.

The present study enabled black-box modeling of the behavior of every observation well when pumping is carried out at well M06. The most simplest structure has been chosen to give the best possible fit for transient and steady state responses at each well, given an excitation at M06. The identified parsimonious model enables easy simulation of the behavior on one hand and on the other, offers simple parameters like gain and time constants to easily interpret connections of observation wells to M06, thus allowing categorization. Moreover, a proper combination of black-box parameters and geometrical ones have shown correlation with hydrogeologically determined characteristics of the aquifer.

The study is not an end in itself and future projects are rather promising. For instance, the handy black-box models can be run in real time to enable supervision. Also, the same approach can be used to consider prediction of solute transfer in the aquifer. Extended to multiple excitations, the approach can account for real situations whereby water levels are modified at two given points on the aquifer for example.

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