Responses to reviewers indicating the changes made according to the line number of the new version of the manuscript.

Response 1 reviewer 1

Dear reviewer,

We thank you for your review and comments; we look forward to providing a satisfactory response.

In L423 (previous version) it is explained why in this study turbulence is not considered a factor that justifies the anomalous behavior, as the flow in groundwater in granular media does not reach the turbulent regime. On the other hand, the subdivision of the well into stretches is done precisely to avoid the influence of differences in skin effects on the flowmeter results (L78) (previous version).

In many of the papers involving USGS technicians that we had reviewed (Keys and Sullivan, 1979; Molz et al., 1990; Hess et al., 1991; Crowder et al., 1994; Gossell et al., 1999; Wilson et al., 2001; Johnson et al., 2005; Lane et al., 2002; Williams, 2008; Garcia et al., 2010; Paradis et al., 2011) we have not found that hydraulic heads differences in the assessment of aquifer permeability in multi-zone wells have been discussed in great detail.

We had not cited Paillet's publications, because we had understood that the methodology shown was largely based on the measurement of flowmeter-logs in ambient condition and with flow rates much lower (<5 l/min = 0.0014 l/s) than the case analyzed in this study. With reference to Paillet et al. (2000, Flowmetering of drainage wells in Kuwait city, Kuwait, Journal of Hydrology, v234, p208) and Paillet (2001, Hydraulic head applications of flow logs in the study of heterogeneous aquifers, Ground Water, v39, p667), the methodology to obtain the different hydraulic heads is not added in our new version, because we could not find the description of the procedure followed to obtain these values.

Following your comments we are going to make the following modification: In L54 "no methodology has been published to quantify its effects" to be more precise, we will add "in water wells in large continental detrital basins".

Below we have added:

"Paillet (1998) showed the results of two flowmeter logs obtained with a heat-pulse flowmeter (lower limit of ~0.1 l/min and upper limit of ~20.0 l/min) in Waupun (Wisconsin, USA). These flowmeter logs were measured under ambient and injection conditions at about 4 l/min, and analyzed for pumping or injection rates typically 1-5 l/min. We think that the relationship used to estimate the transmissivity T_k of each fracture k, starting from the flow into the borehole q_k is: $q_k^b - q_k^a = 2\pi T_k (w^a - w^b) \cdot ln(R_0/r_w)$ where a and b address the ambient and stressed conditions respectively, $w^{a,b}$ are the water levels in the borehole for these condictions, R_0 is the distance to the "outer edges" of the fracture, and r_W is the borehole radius. This relationship does not depend on the unknown value of the far-field head in the aquifer H_k. Later, in Paillet (2000) $\sum T_k \cdot H_k = w^a \cdot \sum T_k$ is used to determine T_k. In this work was stated that: *"the results of high capacity tests, where the effects of ambient hydraulic-head differences would not be significant*", hydraulic head values (4.54, 4.91, 4.91 and 4.91 m below ground level) are presented for the four productive stretches in one of the boreholes analyzed, although the process followed is not reflected in this paper. In Paillet (2000) the hydraulic head estimates (cm above open hole water level) in the same borehole (+28, -11, -11, and -11 cm above open hole water level) are shown. Based on this methodology, Day-Lewis et al. (2011) presented a computer program for flow-log analysis of single holes applicable up to 10 levels, in which the hydraulic head of each zone is determined by minimizing the differences between the flow rates obtained and those of the model, and between borehole's water level and far-field heads."

Following the reviewer's comments, in L256 we added:

"The main differences with the method used by Paillet (1998) are that we have chosen to use the Rehfeldt relationship (Eq. 2) for permeability instead of the Davis and DeWeist relationship (1966) relation for transmissivity, given that the thickness of the layers and the productive sections are taken into account. It has also been considered that the different hydraulic heads are below the static water level (the water level in ambient conditions from Paillet, 1998). The procedure developed is based on the linearity of the hydraulic behavior of the aquifer sections and each section is treated separately."

Response 2 reviewer 1

Dear Reviewer;

We thank you for your review and comments; we attach the response indicating the changes we have made. We are confident that we have given a satisfactory response to your suggestions.

A document has been attached in which the proposed changes are differentiated in red text. In addition, a new figure is included, which was not possible to include in the interactive response.

−) But keep in mind that the corrections to inferred interval transmissivity still involve skin and turbulent inflow contributions, negligible at ultra-low pumping rates. …

In the manuscript, the "skin" effects are mentioned and it is specifically stated that the determination of stretches is made precisely in order not to take into account the different values that these effects may take in each screen.

As mentioned in the manuscript, the groundwater flow does not become turbulent even for the maximum flow rate used (for which the groundwater velocity has been calculated in those vicinities, in particular, for a radius equal to that of the well).

−) The ability to infer head differences in situ for multi-level aquifers has a lot more application than just correcting measured transmissivity for the presence of those head differences.

−) But even more relevance can be added by citing the need to understand the large-scale structure of aquifers concerning recharge …

In discussion section, L-533, we have added:

“This study has allowed to carry out the hydrological and hydraulic division of the studied basin that had not been done before, and such division involve a more precise obtaining of the permeability values in each stretch (and hence in its corresponding aquifer) which was neither been before. Certainly, the new procedure developed to obtain the hydraulic head differences in heterogeneous granular basins and the results obtained for the first time in the Madrid basin may allow hydrogeological hypotheses to understand the large-scale structure of aquifers concerning recharge. According to the results obtained, the fact that the Madrid Basin is considered a single aquifer should be replaced, at least from a depth of 200 m, by a sequence of stretches -aquifers- differentiated by their different permeability values. From 345 m depth (the one of stretch 4), it was also found that the aquifers corresponding to stretches 4, 5 and 6 have different "hydraulic heads" than the upper aquifers. One hypothesis would be that this means different "recharge pathways". So that it could be deduced that above 345 m the Madrid Basin can be considered a single heterogeneous aquifer (with different sub-aquifers of different permeability), and below 345 m, the Madrid Basin consists of a sequence of confined aquifers (the last three coarse-grained ones shown in the well-logs, see Fig. 4) that are hydraulically separated from the rest of the aquifers.

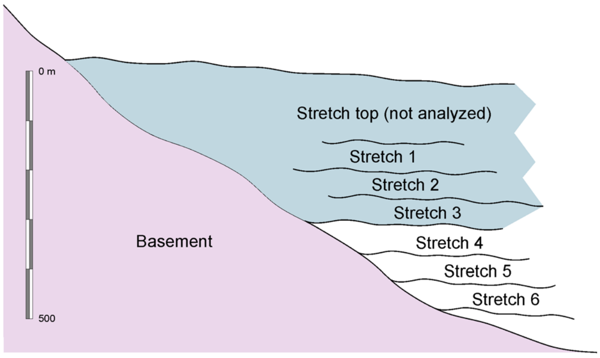


Figure 10. Large-scale scheme of NW arc of the Madrid basin

It should be emphasized that the hydrogeological hypotheses that can be made as the previous scheme must be contrasted with results in more wells within the NW arc of the Madrid Basin."

−) … and contaminant communication rather than just a correction to standard ump test evaluations of transmissivity based on the assumption of a single aquifer.

Just next to above text, we have added:

"The division of the studied well also allows proposing a strategy regarding the arsenic propagation in the Madrid basin. The obtained results indicate the stretch of the studied well that is "activated" when the dynamic level exceeds the "hydraulic head" of the aquifer to which it corresponds, is the rather connected to a point -or zone- where the arsenic focus is. As the exploitation of that stretch in different points of the basin will cause the contaminant to move towards those points, that critical dynamic level should be not allowed."

Response reviewer 2

Dear Reviewer;

We thank you for your review and comments; we attach a detailed response indicating the changes we have made considering all suggestions. We are confident that we have given a satisfactory response to your suggestions, and we are grateful for the exhaustive review of the manuscript, which has allowed us to correct some mistakes and clarify some issues.

A document differentiating the proposed changes in red text has been attached. In addition, the modified and new figures, which could not be included in the interactive response, are included.

In response to the issues raised by the reviewer general comments:

- It is not clear in the writing if this procedure is mandatory for getting reliable information.

Following reviewer's recommendation, at the beginning of the subsection 2.3 we have added:

"The need for an exhaustive treatment of the flowmeter logs arose initially to avoid doubts on observed anomalies in the characteristic curves of the step-drawdown test could stem from the reliability of the flowmeter log results. Thus, it had to be shown that such effects were not due to head losses along the well. In addition, considering that the flow velocity used in the Darcy-Weisbach equation is raised to a power of two, the differences between the head losses resulting from considering the actual flow velocity instead of the velocity directly measured by the sonde is greatly amplified."

in the following paragraph we have replaced

"One of the necessary steps is to process the flowmeter logs, this will be done according to the laws of pipe hydraulics using the methodology developed by Díaz-Curiel et al. (2020)"

by:

"This exhaustive process of the flowmeter logs will be done according to the laws of pipe hydraulics using the methodology developed by Díaz-Curiel et al. (2020)"

- One can doubt on the usefulness of all that stuff in small wells.

At the end of section 2 we have added:

"Applying the rigorous formulation presented to process the flowmeter logs (Eqs. 3 to 7) and considering that the sonde has a significant diameter (r_D), the values of $\langle V \rangle / V(r_D)$ vary between 0.85 and 0.94. This difference represents a 20% error in the total range of variation of that velocity ratio between 0.5 for laminar flow and 1.0 for fully turbulent flow. However, if the well diameter is smaller (close to the diameter of the sonde), $V(r_D)$ approaches Vmax, resulting that the $\langle V \rangle / V(r_D)$ ratio presents a greater variation (from 0.50 to 0.83) for the range of Re found in the case studied, than if the diameter of the well analysed is close to 0.2 m as in the case studied in this work."

- Not that much tricky but absolutely not clearly explained at all in the paper… especially in Section 4.6, on the way they derive conductivities from local measurements of flow rates (from flow logs) and an overall head drawdown between the monitored well and a distant location.

Following the reviewer's recommendation, several changes have been introduced in sections 3, 4.3, 4.4, 4.5 and 4.6.

1) In section 3, L-248, the following changes have been made:

"In most flowmeter logging with several pumping steps, the drawdown used in the Thiem (1906) equation is the same for all of the aquifer stretches in a well, $d_0(\text{s}) = h_{\text{DL}}(\text{s}) - H_{\text{SL}}$ where $h_{\text{DL}}(\text{s})$ is the dynamic level for the 's' pumping step and H_{SL} is the dynamic level of the entire well. However, under the hypothesis presented in this work, the hydraulic head of each stretch, and therefore the corresponding drawdown, can be different. Numerically, the drawdown of each flow stretch τ_{N} will be given by the following relation:

$$d_{\text{N}}(\text{s}) = h_{\text{DL}}(\text{s}) - h_{\text{SL}}(\text{N}), \qquad (8)$$

where $h_{\text{SL}}(\text{N})$ is the static level for flow stretch τ_{N}. In short, the proposed method consists of replacing the single drawdown d in Eq. (2) from Rehfeldt by a drawdown for each stretch."

2) In L-264, we have corrected

"The proposed method for obtaining the hydraulic head of each flow stretch is to 1) correct the drawdown values of the total head loss due to flow along the pipeline and 2) modify the height of the hydraulic head for each flow stretch until the straight line fitted to the data, $q_{\text{N}}(\text{s})$ versus $d_{\text{N}}(\text{s})$, reaches the maximum regression coefficient (where $q_{\text{N}}(\text{s})$ is the water input in flow stretch N for the s pumping step)."

3) In section 4.3, L-344, we have added:

"The static level H_{SL} was measured at a depth of 157 m before the beginning of flowmeter logging. Flowmeter logs were obtained for pumping rates of 20 l/s (measured dynamic level at 172 m), 30 l/s (dynamic level at 178 m), and 70 l/s (dynamic level at 205 m). The drawdowns of the entire well for each pumping rate, without including the head losses, hence are 15 m, 21 and 58 for 20 l/s, 30, and 70 respectively.

4) In section 4.4, L-375, we have added:

"The obtained values of the head loss $\Delta h(\text{s})$ for each pumping rate are shown in Table 2, which will be used in the calculation of the effective drawdown produced."

In L-379, we have added:

Table 2. Head loss values for each pumping rate in the case study

Q (l/s)	$\Delta h(\text{s})$ (m)
20	0.06
30	0.92
70	5.42

5) In section 4.5, table 3, we have the next changes:

Table 3. Water inputs of flow stretches for different pumping rates and fractions over the total flow rate Q_{T} in the case study.

		Pumping rate Q_T (l/s)					
		20		30		70	
Stretch	Depth (m)	Input (l/s) $q_\mathrm{N}(20)$	% of Q_T	Input (l/s) $q_\mathrm{N}(30)$	% of Q_T	Input (l/s) $q_\mathrm{N}(70)$	% of Q_T
Top	0 - 200	10.2	0.53	14.8	0.49	44.5	0.64
T_1	203 - 250	7.0	0.34	9.8	0.33		
T_2 (*)	250 - 300	0.4	0.02	0.4	0.01	0.8	0.01
T_3	300 - 360	1.1	0.06	1.7	0.06	3.8	0.05
T_4	360 - 400	−0.9	−0.05	0.1	0.00	5.8	0.08
T_5	400 - 430	−0.3	−0.02	0.4	0.01	4.6	0.07
T_6	430 - 470	1.6	0.08	2.9	0.10	10.5	0.15

(*) As cited above, this flow stretch is not analyzed because its water inputs are very low for all pumping rates

6) In section 4.6, the following changes have been made:

In L-428 we have added the explanation of the calculation of permeability, which, as the reviewer rightly points out, had not been specified.

“The permeability of each stretch has been calculated using Eq. (2). Instead of the contribution of each layer q_j, the sum total of the contributions of each stretch q_N(s) is considered (see table 3). The unique initial drawdown d considered in Eq. (2) has been modified by the drawdown of the entire well $d_0(\mathrm{s}) = h_\mathrm{DL}(\mathrm{s}) - H_\mathrm{SL} - \Delta h(s)$ for each pumping rate (s) ($\Delta h(s)$ being the head losses showed in table 2). The static level H_SL is 157 m (as determined before the flowmeter logging was conducted) and the dynamic levels $h_\mathrm{DL}(\mathrm{s})$ are 172 m for pumping rate of 20 l/s, 178 m for pumping rate of 30 l/s y 205 m for pumping rate of 70 l/s. The thickness of each layer $\Delta \mathrm{z}_\mathrm{j}$ has been replaced by the thickness of each stretch $\Delta \mathrm{z}(\mathrm{T}_\mathrm{N})$ (depth intervals in Table 3). The radius of influence (R_0) considered is 950 m (as in the previous calculations), and the well radius (r_w) is 0.404/2=0.202 mm. The characteristic curves of each stretch are shown in Fig. 9.a.”

Following the reviewer's comments on Fig. 6, the axes of the graph in Figure 9 have been inverted, being now d_N(s) versus q_N(s). A new figure has also been added (Fig. 9.a) showing the resulting curves considering a unique hydraulic head for all stretches. It should be noted that by inverting the axes (d_N(s) versus q_N(s) instead of q_N(s) versus d_N(s)), the coefficients of the fitting curves are the inverse of those shown in the old figure.

7) In the paragraph of L-436 we have made the following changes:

“Analyzing the specific capacities of different flow stretches, T_1 and T_3 show the expected proportionality for a confined aquifer. However, this is not the case for flow stretches T_4, T_5 and T_6, whose d_N(s) versus q_N(s) data fit to a power function with exponents of 0.22, 0.37 and 0.67, respectively (see Fig. 9.a). Not only does this not reflect Darcian behavior, but it also indicates an exponent p in the Jacob equation of less than 1, as is the case with the well as a whole (see Fig. 6).”

8) In the paragraph of L-440 we have made the following changes:

“However, if it is considered that flow stretches T_4, T_5 and T_6 have different hydraulic heads, the results vary. Through an iterative process, the value of the static level (hydraulic head) of each flow stretch for which the total water input of the flow stretch versus the drawdown acquires greater alignment can be determined. This means that when the data are fitted to a straight line, the regression coefficient is maximum. In other words, the resulting exponent in the Jacob equation when the data are fitted to a power function is p=1. Thus, for flow stretch T_6, the static level for which inputs versus drawdown acquire greater alignment occurs at a depth of 165 m. Similarly, the resulting static level for flow stretch T_5 is located at a depth of 175 m. For a pumping rate of 70 l/s, flow stretch T_4 undergoes an “activation” effect (even higher than flow stretch T_5) when the dynamic level exceeds the true static level of T_4, which is computed at a depth of 177.5 m. Summarizing, the hydraulic heads h_SL(N) obtained with this criterion are 157 m for T_1 and T_3; 177.5 m for T_4; 175 m for T_5; and 165 m for T_6.”

9) In L-449 we have added:

"Figure 9.b shows the regression lines of water inputs versus drawdown for each stretch, with the corresponding relationships and R^2 coefficients"

New Fig. 9 and its caption:

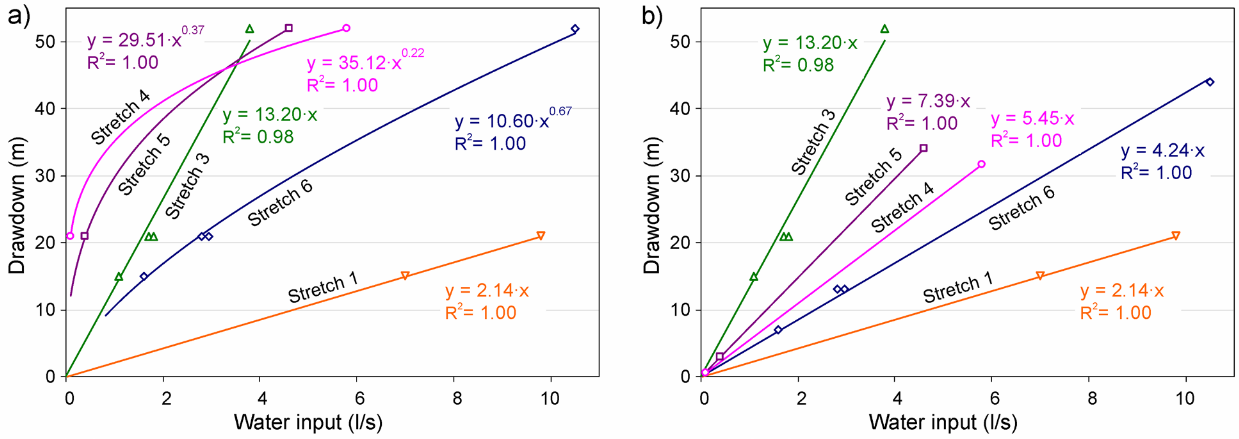


Figure 9. Drawdown versus water inputs for different flow stretches in the case study. a) d_N(s) # q_N(s) with a unique hydraulic head for all the stretches. b) d_N(s) # q_N(s) with the modified hydraulic heads for each stretch obtained considering that p is at least equal to one in the Rorabough equation).

10) In L-455, the next changes have been added:

With these differentiated static levels, the hydraulic conductivities of each flow stretch were obtained using a next change of Eq. (2) (Rehfeldt et al. 1989) replacing $d_0(s)$ by $d_N(s) = h_{DL}(s) - h_{SL}(N) - \Delta h(s)$, which values are presented in Table 4.

Next, we have added:

The successive relationships used to arrive to the actual permeability with depth have been:

$$\left|\begin{array}{c}\text{Thiem (1906)}\\ k=\dfrac{Q}{2\cdot\pi\cdot b\cdot d}\ln\dfrac{R_0}{r_w}\end{array}\right| \rightarrow \left|\begin{array}{c}\text{Rehfeldt et al. (1989)}\\ k_j=\dfrac{q_j}{2\cdot\pi\cdot\Delta z_j\cdot d}\ln\dfrac{R_0}{r_w}\end{array}\right| \rightarrow \left|\begin{array}{c}\text{Adapting to stretches}\\ k_N(s)=\dfrac{q_N(s)}{2\cdot\pi\cdot\Delta z(T_N)\cdot d_0(s)}\ln\dfrac{R_0}{r_w}\end{array}\right| \rightarrow \left|\begin{array}{c}\text{With actual } T_N \text{ hydraulic heads}\\ k_N=\dfrac{q_N(s)}{2\cdot\pi\cdot\Delta z(T_N)\cdot d_N(s)}\ln\dfrac{R_0}{r_w}\end{array}\right|$$

It must point out that the k_N is the same for the different (s) because the ratio $q_N(s)/d_N(s)$ is the same for any pumping rate ($d_N(s)$ versus $q_N(s)$ are fitted to a straight line).

11) In table 4, the next changes have been made:

Table 4. Specific capacities and permeabilities of flow stretches for the static level determined in the case study

Stretch	$h_{SL}(N)$ (m)	$q_N(s)/d_N(s)$ (m^2/s)	k (Darcy)
Top	157.0	-	-
T1	157.0	$4.7\cdot10^{-4}$	$1.3\cdot10^{-3}$
T2	157.0	-	-
T3	157.0	$7.5\cdot10^{-5}$	$2.0\cdot10^{-4}$
T4	177.5	$1.8\cdot10^{-4}$	$5.3\cdot10^{-4}$
T5	175.0	$1.4\cdot10^{-4}$	$5.4\cdot10^{-4}$
T6	165.0	$2.4\cdot10^{-4}$	$1.0\cdot10^{-3}$

12) Sentence in L-463 has been modified as follows:

"The average hydraulic conductivities of the stretches in the studied part of the well (200 to 470 m) have values between $2\cdot10^{-4}$ and $1.3\cdot10^{-3}$ Darcy, providing a geometric mean value of $5\cdot10^{-4}$ Darcy, which is close to the average hydraulic conductivity obtained with the pumping tests."

Specific Comments

- Line 96. Not well said. A single scalar value (that of a conductivity in a layer) is always proportional to another one (that of the whole wellbore) up to a multiplying constant: a = (a/b)*b!

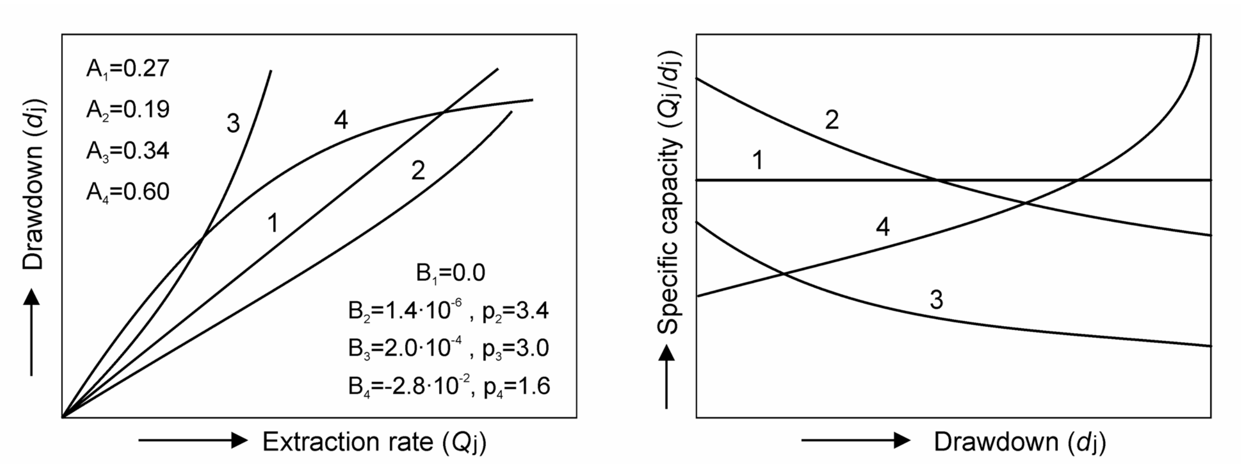
We appreciate the reviewer's recommendation; we have added the following in L-113:

"To achieve hydraulic interpretation from flowmeter logs, most authors (Molz et al., 1989; Rehfeldt et al., 1992; Ruud and Kabala, 1996; Zlotnik and Zurbuchen, 2003a; Barahona-Palomo, et al. 2011; Riva et al., 2012) start from the basis that hydraulic conductivity values for each permeable layer (from each screen) are proportional to the hydraulic conductivity of the entire well up to a multiplying constant."

- Fig. 1-left (or Fig. 6). I would have swapped in one of the figs the horizontal and vertical axis, so they can read exactly the same way without leaning the head at 90° in Fig 1-left, to find the same plot as in Fig-6.

By the way, in Fig. 1-left the coefficient "A1" = 0.6 should read "A4" = 0.6.

Many thanks for the correction; we have replaced A1 by A4.



We appreciate the reviewer's suggestion. We have opted to modify the Fig. 6 (instead Fig 1-left as proposed by reviewer) because it is easier to recognize the Jacob (1947) or Rorabaugh, (1953) behavior ($d=A\cdot Q+B\cdot Q^p$). We have divided figure 6 in two graphs, one with the drawdown in ordinates versus pumping rate, and the other with the drawdown in abscissas versus specific capacity.

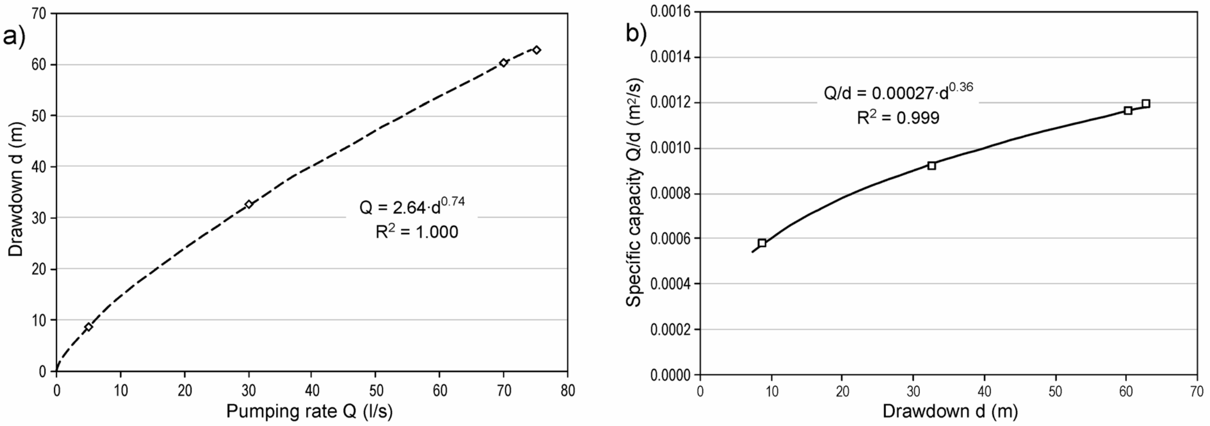


Figure 6. a) Drawdown versus the pumping rate, b) and the specific capacity versus drawdown in the case study.

- Line 180. Specify which terms are involved in the Reynolds number, especially the “length” that I guess to be the diameter (radius) of the well.

  Following the reviewer's recommendation, we have added in L203:

  “It begins by taking the measured velocity V_{meas} at a given depth as the initial flow velocity and the initial Reynolds number $\mathrm{Re}_{\mathrm{ini}}$ according to its definition, that is, $\mathrm{Re}=\rho\cdot<V>\cdot D/\mu$, where ρ is the water density, D the well diameter and μ the dynamic viscosity.”

- P. 7, Fig. 2. Specify that k in the notations Re_k is the iteration index of the convergence algorithm, and not anything else.

  We appreciate the reviewer's recommendation. We have modified the subscript of Re according to the one used in Figure 7 and we have added the following clarification in L-209:

  “Then, using the relationship for the velocity factor $F_{\mathrm{vel}}(\tau)$, defined as the ratio between Vmax and the flow velocity $<V>$, the first flow velocity is obtained with the corresponding Reynolds number $\mathrm{Re}_{\mathrm{ini}}$, which is closer to the actual value. Applying $\tau(\mathrm{Re})$, $V(r_D)$, and $F_{\mathrm{vel}}(\tau)$, a new Re value Re_k is obtained (k being the iteration index of the convergence algorithm). This process is repeated until a given convergence criterion c_{CR} is reached, following the flow chart in Fig. 2 (adapted from Díaz-Curiel et al., 2020), to obtain Re(z).”

- Line 200, Eq. 7. Please also remind the form employed for the Darcy-Weisbach equation. Several form exist, even if one can guess that in here the form is: Gradh (or Deltah) = (f/2g)*(V^2/D) (D effective diameter of the well, g gravity, V water velocity, and f friction factor).

  Following the reviewer's recommendation, we have added in L-221-224:

  “Once the Reynolds number at each depth is known, the head loss can be obtained by the Darcy-Weisbach equation (Darcy 1857; Weisbach 1845), given by $\Delta h=f\cdot(\ell/D)\cdot(<V>^2/2g)$, where g is the gravity acceleration $(\mathrm{m\cdot s^{-2}})$, $<V>$ is the average flow velocity $(\mathrm{m\cdot s^{-1}})$, D is inner diameter of the well (m), ℓ is the length of each considered pipe element (m), and f the friction factor (dimensionless) for smooth pipes given by Eq. (7):”

- P. 13, Table 2. Not clear how the deltah in the table are calculated. Is that a mean from bottom to top handling a mean friction factor and a mean velocity over the whole depth investigated? Or is that (what I think better) the cumulated Delta h adding the successive local delta values relying upon local friction factors and local water velocities?

  The reviewer is right in his assessment, and to make it clearer we have added in L-373:

  “The total head loss below the pump is obtained by integrating the head loss throughout the well based on the flow velocity obtained at each depth (see Fig. 7), that is, the cumulated Δh adding the successive local head loses values relying upon local friction factors and local water velocities.”

  Reviewing the manuscript, we have noticed an error in L-382:

  “In this case, the friction factor reaches values six times higher at the bottom of the well than at the initially recorded depth, and the value of the head loss is low (0.006 m) because …”

  would be:

  “In this case, the friction factor reaches values six times higher at the bottom of the well than at the initially recorded depth, and the value of the head loss is low (0.06 m) because …”

- P. 15, Fig.8-a (the three left plots). It I unclear to me what mean the alternating grey and white bars beneath (left to) the three curves. They do not seem to be the alternation of geological layers, as they are not the stretches (#1 to #6) reported in Fig. 8-B (the three right plots). Do they correspond to intervals where the monitored velocities in the flow logs are quite uniform?

  This was not its purpose. The bars only reflect the depth intervals of each screen (we segmented the measured continuous logs with vertical segments thinking that it reveals that flow only increases in screens, and it better shows the flow steps between them, but if you think we should return the bottom and top points of the flow rate in each screen to its center, please let us know). To clarify this, we have added in the caption of Figure 8:

  “Figure 8. Flowmeter results in the case study (grey horizontal bars reflect the depth intervals of each screen). a) upward flow rate versus depth; b) water inputs from each screen.”