Hydrodynamic characterization of carbonate aquifers by atypical pumping tests without interruption of drinking water exploitation

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Abstract

The Gran Sasso carbonate aquifer is the largest and most productive in the Apennines. Its hydrogeological structure has been studied since the middle of the last century for springs’ characterization for drinking purposes and for a motorway tunnel. Meanwhile, its hydrodynamic parametrization is less developed and is limited to monitoring the discharge and chemical and isotopic parameters. Secondary porosity characterizes the aquifer, and an underlying impermeable marly complex represents the basal aquiclude. It might appear inappropriate to characterize the hydraulic properties via pumping tests, as their reliability is proven in homogeneous and isotropic media. However, the high extent of the aquifer, the wells’ location, the scarcity of information available and the lack of alternatives forced to estimate hydrodynamic parameters as in porous aquifers and to test the aquifer experimentally, especially in maximum pumping conditions. Since the aquifer testing was performed during the normal well field’s activities, it was not possible to perform typical tests. Therefore, the step-drawdown test was obtained by turning on an increasing number of wells over time and keeping fixed the observation points. As results, hydraulic conductivity, transmissivity, drawdown in operating condition, the influence radius and the flow directions have been obtained, without interrupting the water supply.

Introduction

Carbonate fractured aquifers are used for groundwater supply in several regions of the world [1] however, the characterization of their hydrodynamic properties is always challenging.

The exploitation of the carbonate aquifer of the Central Apennines has begun during the 60s and 70s of the last century for big aqueducts for serving millions of people. During that period, the Italian government had set up an organization (“Cassa per il Mezzogiorno”) for research, study, and springs’ exploitation for drinking purposes [2–4]. The considerable economic resources had been used for boreholes and in some of them, pumping test for aquifer characterization had been executed.

During 80s, 90s, and 2000s, following the increased demand for drinking water, have implemented the exploitation of the Apennine carbonate aquifers; consequently, many wells were built thanks to the high availability of groundwater [5], but with lower the scientific precision than that of the “Cassa per il Mezzogiorno”.

Nowadays, regulation about groundwater and the increasing sensibility about sustainable use of water resources as well as the influence of climate change on groundwater [6–8] require a greater and deeper hydrogeological and hydrodynamic knowledge of aquifers. On the other hand, this necessity is contrasted by the logistical and economic unavailability of managing authorities for the execution of pumping tests; the logistical issues are due to the impossibility to halt the water withdrawal and the distribution of drinking water.

This study wants to contribute to tackle the described issue, which is typical for the entire Central-Southern Apennines, using the same existing well fields’ set-up.
The case study is about the Gran Sasso aquifer one of the most important in Central Italy [5] which has been studied for engineering purposes and for springs’ characterization; from a hydrodynamic point of view, the available data are referred only to discharge, chemical and isotopic features [9–10]. The lack of hydrodynamic data and the presence of well fields have allowed the execution of atypical step-drawdown test using the exploited wells, both for pumping and head monitoring.

Usually, pumping tests are mainly used in porous aquifer because of their homogeneity and isotropy which cannot be found in fractured aquifers, where the flow is controlled by heterogeneity [11]. A typical pumping test involves a well pumping at constant rate and drawdown monitored through time in one or more observation wells; the test results are displayed as time vs drawdown curves which are used for parameters estimation. The step-drawdown test is particular kind of pumping test, where the pumping rate is increased when the system reaches steady-state, and the drawdown is no longer present in the pumping well. In the present study, the pumping rate raise has been obtained turning on an increasing number of wells. During the tests the water service has not been halted.

**Materials and methods**

**Site description**

The study site is located at the foot of the Apennines chain, in Abruzzo Region, inside the Tirino River valley (Fig. 1), where the carbonate formations meet the marly-arenaceous foredeep deposits. In details, in this area a superposition between the Gran Sasso carbonate unit and the Morrone – Roccatagliata, through trust faults which involve the marly - arenaceous Laga Formation, can be observed. In this framework, the Tirino river valley has been created by an extensional tectonic and filled by Quaternary deposits, such as lacustrine, detrital, and strictly alluvial one.

From the hydrogeological point of view, this area hosts the most important aquifers of the Abruzzo Region, the Gran Sasso aquifer, 700km²-wide [5], and the Morrone aquifer [12]. As abovementioned, these units are mainly calcareous and then characterized by high hydraulic conductivity due to fracturing and karstification and with wide recharge areas. The Quaternary deposits’ hydraulic conductivity changes according to the grain size, consequently they allow water flow or create local aquicludes.

In the lowest areas, where the carbonate structures are in contact with the marly ones, these aquifers generate basal springs whose discharges are between 6 m³/s and 1 m³/s; thus, the Tirino is an almost exclusively spring-fed river with a length of 13 km and a streamflow of over 12 m³/s [13]. The main springs are Basso Tirino one (Q ~ 6 m³/s), the Capo d’Acqua springs group (Q ~ 3 m³/s), and Presciano (Q ~ 2 m³/s) ones (Fig. 1); furthermore, minor springs (Q ~ 1 m³/s) are also present and called Incrementi Medio Tirino [13].

According to literature data [14] the total spring discharge of the area is 13 m³/s derived from the previous springs and from riverbed increases from other sources.
Locally the geological and hydrogeological framework is quite complex because of heterogeneity of the deposits; from literature data and available boreholes’ stratigraphies [15–18], in Fig. 2 the detailed hydrogeological set-up of the study area is shown: the Gran Sasso carbonate complex is in contact with the marly – clayey one creating a no-flux hydrogeological limit.

**Well field set-up**

The *San Rocco* well field (Fig. 2) is on the left side of the Tirino river with eight wells and a piezometer (Pz) which draw water for drinking purposes; the global pumping rate varies through seasons depending on the request and on the availability of other water sources such as springs. The pumping rate is usually over 700 l/s, except during spring (April and May) where it is 200 l/s. A smaller well field (*Piazzale di Bussi*), located close to San Rocco one, is used to integrate water request during late summer and fall with a 100 l/s pumping rate.

For monitoring reasons, a piezometer 1 km-far from the field has been also considered, the *Cartignano* one.

The eight *San Rocco*s wells have been approximated to a single well called Equivalent Well (EW), to define its position, the single pumping rates and the locations of all the *San Rocco* wells have been considered (Fig. 2).

**Step-drawdown test**

Usually pumping tests are not suitable for carbonate aquifer like this, where hydraulic conductivity is due to fracturing and karstification, however a step-drawdown test has been performed and the equivalent hydraulic parameters have been estimated considering the aquifer like a porous one, as well as the influence radius, when the pumping rate was maximum.

The step drawdown test was described by Jacob [19], it implies to observe the drawdown in a well while the pumping rate is increased by step [20]; in each step the discharge rate is kept constant, and it is increased when the steady state is reached.

The step-drawdown test schedule, for this study, is shown in Table 1 and organized to avoid the interruption of drinking service.
As can be seen, the water distribution has been turned off for only 2 hours for the recovery step, and to obtain the so called “initial steady state”, then for each step an increasing number of wells have been switched on, keeping fixed the monitoring wells and piezometers; each step lasted at least 24 hours.

After the step-drawdown end, the water level has been monitored for 114 days from the beginning of the third step; this has allowed the summer period monitoring when the pumping rate is the same of the third step (740 l/s). Only small adjustment in drawdown have been recorded probably due to switch-on and switch-off of the Piazzale di Bussi well field with a pumping rate of 100 l/s.

**Data elaboration**

Considering the available atypical data and the derived approximations, two of the simplest and consolidated methods have been chosen for data elaboration.
For the steady-state Dupuit method have been used, while for the unsteady-state, the Theis one; both approaches have allowed the hydraulic conductivity and influence radius estimation.

The Dupuit theory [21] considers a radial flow in a well pumping at constant rate \( Q \) and the spreading of a depression cone until a certain distance (influence radius) where the drawdown is null because of the equilibrium between pumping and aquifer response.

Some conditions must be present, such as the steady-state conditions, which means that in each point of the aquifer the velocity vector must be constant in time, aquifer has to be homogeneous and isotropic, Darcy law [22] must be valid, the flow has to be horizontal and the same velocity in a vertical section is needed.

The Dupuit equation can be applied to both phreatic and confined aquifer and in this specific case, the aquifer has been considered as phreatic (Fig. 3) and the Dupuit equation is

\[
Q = 1.366 K \frac{h_0^2 - h_w^2}{\ln r_0 / r_w} 1
\]

where \( Q \) is the pumping rate (m\(^3\)/s), \( r_0 \) is the distance between the pumping well and the no drawdown point, \( r_w \) is the pumping well radius, \( h_0 \) and \( h_w \) are the saturated thickness in static condition and the saturated thickness in the pumping well, respectively.

If two observation wells are considered, Dupuit – Thiem equation [23] can be applied

\[
Q = 1.366 K \frac{h_2^2 - h_1^2}{\ln r_2 / r_1} 2
\]

consequently, the equation for the hydraulic conductivity \( K \) estimation is

\[
K = \left( \frac{Q}{1.366} \right) \log \frac{r_2}{r_1} / \left( h_2^2 - h_1^2 \right) 3
\]

where \( Q \) is the pumping rate (m\(^3\)/s), \( r_1 \) is the distance between the observation well P1 and the pumping well, \( r_2 \) is the distance between the observation well P2 and the pumping well, \( h_1 \) and \( h_2 \) are the saturated thickness in the observation wells P1 and P2 with static conditions, respectively (Fig. 3).

The estimation of the influence radius \( r_0 \) has been carried out using two equations, the Dupuit [21] and the Sichardt [24] ones.

The Dupuit equation is

\[
\ln r_0 = \left( \frac{h_0^2 - h_1^2}{h_2^2 - h_1^2} \right) \left( \ln \frac{r_2}{r_1} \right) + \ln r_1 4
\]

while the Sichardt equation is
\[ r_0 = 3000 \left( h_0 - h_w \right) \sqrt{K} \]

where \( r_1 \) is the distance between the observation well P1 and the pumping well, such as \( r_2 \), \( h_0 \) is the water table depth in static condition, \( h_w \) is the hydraulic head in the pumping well, and \( h_1 \) and \( h_2 \) are the hydraulic heads in the observation wells P1 and P2 with static conditions, respectively.

Taking into account the thickness of the aquifer, transmissivity \((T)\) can be also estimated, using

\[ T = K b \]

where \( K \) is the hydraulic conductivity and \( b \) the aquifer thickness.

In this study, for data elaboration, the abovementioned Equivalent Well (EW) has been considered as pumping well, \( P5, P6 \) wells, Cartignano, Piazzale di Bussi and San Rocco piezometers, as monitoring wells.

The unsteady theory by Thies \([25]\) is based on the principle that if pumping continues a wider portion on the aquifer is involved in it, as consequence there is not a fixed influence radius, but it becomes bigger as well as the depression cone.

Considering the big aquifer extension \([5]\) and the low drawdown compared with the aquifer thickness, in this case the carbonate aquifer has been considered as confined and the Theis equation applied,

\[ h_0 - h = \frac{Q}{4\pi T} \int_0^\infty \frac{e^{-u}du}{u} \]

where \( u = \frac{r^2}{4Tt} \) and \( \int_0^\infty \frac{e^{-u}du}{u} = W(u) \) called Well function, \( h_0 \) is the hydraulic head at a distance \( r \) from the well, \( h \) il the hydraulic head after a certain time \( t \), \( Q \) the pumping rate \((m^3/s)\), \( T \) the transmissivity and \( S \) the storage coefficient.

This method can be applied if the aquifer is homogeneous and isotropic, it is confined with constant thickness and the well goes through all the aquifer thickness with an infinitesimal diameter \([26]\).

The Eq. \((7)\) can be solved using the Jacob – Cooper approximation \([27]\) and it becomes

\[ h_0 - h = \Delta h = \frac{0.183Q}{T} \left( \log \left( \frac{2.25Tt}{r^2S} \right) \right) \]

where \( \frac{0.183Q}{T} = C \) and it is the angular coefficient of the line "Drawdown vs Log time".

**Hydrochemical parameters**

Temperature \((T)\), pH, electrical conductivity \((\chi)\) and redox potential \((Eh)\) have been monitored with a portable multiparameter probe during the pumping tests in order to identify any variation in physico -
chemical features due to expansion of the cone or involved portions of aquifer with different lithological characteristics and consequently different water rock interactions. These parameters have been measured in \( P2 \).

**Consideration about the atypicality of the test**

This test has been defined atypical because of the use of some approximations:

- the well field was pumping water during the test;
- the pumping rate was increased using a higher number of pumping well instead of rising a single one;
- the pumping rate for each step has been decided by the managing organization base on the features of the available pumps;
- this method has been applied to a carbonate aquifer considering it like a porous one;
- the conceptual model (Fig. 3) has been simplified compared to the reality;
- the data elaborations have been executed using an Equivalent Well, instead of a single one.

**Results**

**Step-drawdown test, steady-state condition**

During the execution of the step-drawdown test \( P5, P6 \) wells and \( \text{San Rocco, Piazzale} \) and \( \text{Cartignano} \) piezometers have been monitored (Fig. 4 and Table 2); the geometry of the aquifer has been simplified and, in static condition, a 57 m – saturated thickness has been considered. Moreover, the unstoppable water exploitation and the use of the well field pumps for the test, have not allowed the execution of the “typical steps” for the step-drawdown test; indeed, in this case the pumping rates have been decided on the basis of the single pumping rate of each pump. In Table 2 the pumping rates of each step can be observed, the step 2 has been divided into two sub-steps because of the working well field.
Table 2
– Step-drawdown test results.

<table>
<thead>
<tr>
<th>Well/Piez</th>
<th>Step</th>
<th>Pumping rate (l/s)</th>
<th>Distance from EW (m)</th>
<th>$h_1$ (m)</th>
<th>$h_2$ (m)</th>
<th>$\Delta h$ (m)</th>
<th>$\Delta h_{TOT}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P5</strong></td>
<td>Recovery</td>
<td>0</td>
<td>11</td>
<td>57.51</td>
<td>57.00</td>
<td>-0.51</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>453</td>
<td>11</td>
<td>57.00</td>
<td>56.68</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>522</td>
<td>11</td>
<td>56.68</td>
<td>56.57</td>
<td>0.19</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>560</td>
<td>11</td>
<td>56.57</td>
<td>56.39</td>
<td>0.10</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>11</td>
<td>56.39</td>
<td>55.50</td>
<td>0.89</td>
<td>1.50</td>
</tr>
<tr>
<td><strong>P6</strong></td>
<td>Recovery</td>
<td>0</td>
<td>27</td>
<td>57.72</td>
<td>57.00</td>
<td>-0.72</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>453</td>
<td>27</td>
<td>57.00</td>
<td>56.88</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>522</td>
<td>27</td>
<td>56.88</td>
<td>56.82</td>
<td>0.06</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>560</td>
<td>27</td>
<td>56.82</td>
<td>56.71</td>
<td>0.11</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>27</td>
<td>56.71</td>
<td>49.17</td>
<td>7.54</td>
<td>7.83</td>
</tr>
<tr>
<td><strong>San Rocco</strong></td>
<td>Recovery</td>
<td>0</td>
<td>54</td>
<td>57.87</td>
<td>57.00</td>
<td>-0.87</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pz</strong></td>
<td>1</td>
<td>453</td>
<td>54</td>
<td>57.00</td>
<td>56.69</td>
<td>0.31</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>522</td>
<td>54</td>
<td>56.69</td>
<td>56.58</td>
<td>0.11</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>560</td>
<td>54</td>
<td>56.58</td>
<td>56.46</td>
<td>0.12</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>54</td>
<td>56.46</td>
<td>55.60</td>
<td>0.86</td>
<td>1.40</td>
</tr>
<tr>
<td><strong>Piazzale di Bussi</strong></td>
<td>Recovery</td>
<td>0</td>
<td>105</td>
<td>57.55</td>
<td>57.00</td>
<td>-0.55</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pz</strong></td>
<td>1</td>
<td>453</td>
<td>105</td>
<td>57.00</td>
<td>56.86</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>522</td>
<td>105</td>
<td>56.86</td>
<td>56.80</td>
<td>0.06</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>560</td>
<td>105</td>
<td>56.80</td>
<td>56.68</td>
<td>0.12</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>105</td>
<td>56.68</td>
<td>55.99</td>
<td>0.69</td>
<td>1.01</td>
</tr>
<tr>
<td><strong>Cartignano</strong></td>
<td>Recovery</td>
<td>0</td>
<td>1158</td>
<td>57.01</td>
<td>57.00</td>
<td>-0.01</td>
<td>-</td>
</tr>
<tr>
<td><strong>Pz</strong></td>
<td>1</td>
<td>453</td>
<td>1158</td>
<td>57.00</td>
<td>57.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2a</td>
<td>522</td>
<td>1158</td>
<td>57.00</td>
<td>57.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2b</td>
<td>560</td>
<td>1158</td>
<td>57.00</td>
<td>57.00</td>
<td>0.00</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>1158</td>
<td>57.00</td>
<td>57.00</td>
<td>0.00</td>
<td>-</td>
</tr>
</tbody>
</table>
In Table 3 hydraulic conductivity estimation is summarized, \( P5 - \text{Piazzale} \) piezometer and \( San \ Rocco - \text{Piazzale} \) piezometers have been taken into account; \( P5 \) has been considered only when it was not working. Eqs. (3) and (6) have been used for hydraulic conductivity and transmissivity estimation, respectively.

Table 3
- Hydraulic conductivity and transmissivity estimation (Pz stands for piezometer).

<table>
<thead>
<tr>
<th>Step</th>
<th>Pumping rate (l/s)</th>
<th>( K ) (m/s)</th>
<th>( K ) (m/s)</th>
<th>( T ) (m(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>453</td>
<td>0.0050</td>
<td>0.0050</td>
<td>0.285</td>
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<tr>
<td>2a</td>
<td>522</td>
<td>0.0044</td>
<td>0.0044</td>
<td>0.250</td>
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<tr>
<td>2b</td>
<td>560</td>
<td>-</td>
<td>0.0048</td>
<td>0.274</td>
</tr>
<tr>
<td>3</td>
<td>740</td>
<td>-</td>
<td>0.0036</td>
<td>0.205</td>
</tr>
</tbody>
</table>

The mean hydraulic conductivity obtained is \( 4.5 \times 10^{-3} \) m/s, while the mean transmissivity is \( 2.5 \times 10^{-1} \) m\(^2\)/s considering an aquifer 57 m thick. Despite the issues faced during the test, results show a good convergence using different pumping rate (different steps) and different well/piezometer couples.

The influence radius has been calculated for each pumping rate, using piezometers data for Dupuit equation [21] and \( P5 \) well for Sichard [24] one.
Table 4
– Influence radius estimation.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Step</th>
<th>Pumping rate (l/s)</th>
<th>( h_2 ) (Piazzale Pz) (m)</th>
<th>( h_1 ) (San Rocco Pz) (m)</th>
<th>( r_0 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dupuit</td>
<td>1</td>
<td>453</td>
<td>56.86</td>
<td>56.69</td>
<td>180</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>560</td>
<td>56.68</td>
<td>56.46</td>
<td>280</td>
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<td></td>
<td>3</td>
<td>740</td>
<td>55.99</td>
<td>55.6</td>
<td>590</td>
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<tr>
<td>Sichard</td>
<td>1</td>
<td>453</td>
<td>57</td>
<td>56.70</td>
<td>64</td>
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<tr>
<td></td>
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<td>560</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>55.50</td>
<td>302</td>
<td></td>
</tr>
</tbody>
</table>

Step-drawdown test, unsteady-state condition

The unsteady-state elaboration has been performed using P5 well, San Rocco and Piazzale piezometers data (Fig. 5); as for the steady-state estimation, the geometry of the aquifer has been considered as 57 m thick. Transmissivity \( T \) has been estimated from Eq. (8), while the hydraulic conductivity from Eq. (6).
Table 5
– Unsteady-state elaboration and results. (For symbols see paragraph “Data elaboration”).

<table>
<thead>
<tr>
<th>Well/Piez</th>
<th>Step</th>
<th>Q (l/s)</th>
<th>C</th>
<th>$t_0$ (s)</th>
<th>T ($m^2/s$)</th>
<th>K (m/s)</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P5$</td>
<td>1</td>
<td>453</td>
<td>0.42</td>
<td>0.20</td>
<td>0.003</td>
<td></td>
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<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>0.18</td>
<td>0.75</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>I log cycle</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td></td>
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<td>0.38</td>
<td>0.36</td>
<td>0.006</td>
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<td>II log cycle</td>
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</tr>
<tr>
<td>$Pz$ San Rocco</td>
<td>1</td>
<td>453</td>
<td>0.39</td>
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<td>0.004</td>
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<td></td>
<td>3</td>
<td>740</td>
<td>0.175</td>
<td>250</td>
<td>0.77</td>
<td>0.014</td>
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<tr>
<td></td>
<td>3</td>
<td>740</td>
<td>0.36</td>
<td>1600</td>
<td>0.38</td>
<td>0.007</td>
<td>0.46</td>
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<tr>
<td>$Pz$ Piazzale di Bussi</td>
<td>1</td>
<td>453</td>
<td>0.21</td>
<td>0.39</td>
<td>0.007</td>
<td></td>
<td></td>
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<td></td>
<td>3</td>
<td>740</td>
<td>0.14</td>
<td>280</td>
<td>0.97</td>
<td>0.017</td>
<td>0.06</td>
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<tr>
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<td>3</td>
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<td></td>
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</tbody>
</table>

The mean transmissivity obtained is $3.3 \times 10^{-1} \ m^2/s$, the mean hydraulic conductivity is $5.6 \times 10^{-3} \ m/s$, while the storage coefficient varies between 0.06 and 0.15 (Table 5).

The test elaborated using the unsteady-state does not show a good convergence like the steady-state one. Anyway, the mean value obtained from the different elaboration, estimated using different log-cycles and piezometers, is perfectly comparable with that obtained from the steady-state calculations.

**Long term observations**

In Table 6 the drawdowns observed after 114 days have been summarized; as can be seen in $P5$, San Rocco and Piazzale di Bussi piezometers the drawdown has slight differences, $P6$ is an exception because a difference of a meter has been observed, this because of the superposition effect during the used of both well field during the summer season.
Table 6
– Long term observations in dynamic conditions.

<table>
<thead>
<tr>
<th>Well/Piezometer</th>
<th>Distance from EW</th>
<th>Head (Steady-state cond.)</th>
<th>Drawdown* (after 5 days)</th>
<th>Drawdown* (after 114 days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P5</td>
<td>11 m</td>
<td>284.06</td>
<td>-2.0 m</td>
<td>-1.3 m</td>
</tr>
<tr>
<td>P6</td>
<td>26.5 m</td>
<td>284.81</td>
<td>-7.8 m</td>
<td>-8.7 m</td>
</tr>
<tr>
<td>Pz San Rocco</td>
<td>54 m</td>
<td>284.48</td>
<td>-1.4 m</td>
<td>-1.3 m</td>
</tr>
<tr>
<td>Pz Piazzale di Bussi</td>
<td>105 m</td>
<td>280.93</td>
<td>-1.0 m</td>
<td>-1.2 m</td>
</tr>
</tbody>
</table>

*compared with static level

Hydrochemical parameters

Looking at Table 7a constant trend can be observed, indeed during the pumping test all parameters have not significant variations except for the redox potential which has values between 126 mV and 223 mV because of the oxygenation due to water exploitation.

This trend indicates a homogenous aquifer from a rock-water interaction point of view and the aquifer portion interested by pumping does not interfere with physico – chemical parameters.

The mean temperature value is 11.8°C, the mean electrical conductivity is 575 µS/cm, and the mean pH is 8.1.
Table 7
- Monitored physico-chemical parameters.

<table>
<thead>
<tr>
<th>Time from test beginning (hour:min)</th>
<th>T (°C)</th>
<th>Χ (µS/cm)</th>
<th>pH</th>
<th>Eh (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.00</td>
<td>12.2</td>
<td>583</td>
<td>8.3</td>
<td>126</td>
</tr>
<tr>
<td>24.15</td>
<td>11.7</td>
<td>580</td>
<td>8.2</td>
<td>155</td>
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<tr>
<td>25.50</td>
<td>11.8</td>
<td>573</td>
<td>8.0</td>
<td>173</td>
</tr>
<tr>
<td>27.00</td>
<td>11.8</td>
<td>573</td>
<td>8.2</td>
<td>144</td>
</tr>
<tr>
<td>29.05</td>
<td>11.8</td>
<td>573</td>
<td>8.1</td>
<td>194</td>
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<tr>
<td>34.50</td>
<td>11.6</td>
<td>579</td>
<td>8.1</td>
<td>155</td>
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<tr>
<td>47.40</td>
<td>11.7</td>
<td>578</td>
<td>8.2</td>
<td>147</td>
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<tr>
<td>50.30</td>
<td>11.8</td>
<td>574</td>
<td>8.1</td>
<td>213</td>
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<tr>
<td>52.40</td>
<td>11.9</td>
<td>574</td>
<td>8.2</td>
<td>223</td>
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<tr>
<td>56.45</td>
<td>11.7</td>
<td>572</td>
<td>8.2</td>
<td>160</td>
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<tr>
<td>72.05</td>
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<td>8.2</td>
<td>178</td>
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<tr>
<td>76.00</td>
<td>11.9</td>
<td>577</td>
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<td>216</td>
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<tr>
<td>78.35</td>
<td>12.0</td>
<td>577</td>
<td>8.1</td>
<td>189</td>
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<tr>
<td>95.45</td>
<td>11.7</td>
<td>535</td>
<td>8.0</td>
<td>164</td>
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</tbody>
</table>

Discussion

Step-drawdown test, steady-state condition

The step-drawdown test results can be analyzed in detail using both Hydraulic head vs Time plot (Fig. 4) and the characteristic curves (Fig. 6). In the first case, as can be seen in Fig. 4, a very fast recovery in well P5 has been recorded, this because of an anomalous response of the well system to pumping: the well casing empties quickly and it is not compensated by the aquifer, so when recovery starts there is a fast filling inside the well casing with a 3.8 m rising in P5.

In Fig. 6 the characteristics curve of each monitored well or piezometer, where Drawdown vs Pumping rate is plotted; as can be noticed, drawdown decreases away from the well field, the curves are parallel to each other despite their distance from the well field, and Cartignano piezometer, located at over 1 km from the well field, is not affected by drawdown; these observations implies that the tested aquifer has homogeneous features.
The water table reconstruction (Fig. 7) points out a west-east flow direction in the San Rocco well field and a north-west/south-east one in Piazzale di Bussi well field; the hydraulic gradient is 0.02 increasing from north-west to south-east.

**Step-drawdown test, unsteady-state condition**

Looking at Fig. 5, the plot “Depth from the ground vs Time” is not a straight line, this because of the unconventional type of test; to carry out the transmissivity the straighter portions of the plots have been considered. The potentiometric map at the end of the third step, 120 hours after the test beginning, is in Fig. 8 and points out the same flow directions of the static conditions.

The water table decrease is restricted to the well fields area with a 1.4 m drawdown in San Rocco well field and 1.0 m in Piazzale di Bussi one when the pumping rate is maximum (Q = 740 l/s); the hydraulic gradient is 0.026 increasing from north-west to south-east.

**Conclusion**

The atypical step-drawdown test in carbonate aquifer has been performed using an increasing number of pumping wells to reach the maximum available pumping rate, without turning off the water exploitation.

The hydrodynamic parameters have been carried out using both steady-state and unsteady-state equations; in the first case the mean hydraulic conductivity is $4.4 \times 10^{-3}$ m/s and the mean transmissivity, with an aquifer thickness of 57 m, is $2.5 \times 10^{-1}$ m$^2$/s. In the unsteady-state condition, the mean hydraulic conductivity is $5.6 \times 10^{-3}$ m/s, the mean transmissivity $3.3 \times 10^{-1}$ m$^2$/s and the storage coefficient ranges from 0.06 to 0.15. The influence radius, calculated using the equivalent well, varies from 300 to 590 m when the pumping rate is maximum.

The data elaboration using the characteristic curves (Fig. 6) has highlight homogeneous features of the aquifer and its hydrodynamic parameters confirmed by the physico-chemical monitoring during the pumping test; the hydrochemical parameters have been constant during all the test with mean values of 11.8°C for temperature, 575 µS/cm for electrical conductivity and 8.1 for pH.

The maximum drawdown, equal to 1.4 m, has been reached after 120 hours from the test beginning and after 72 hours from the application of the maximum pumping rate (740 l/s); the drawdown after 114 days is very similar to the measured during the test, with slight differences when the Piazzale di Bussi well fields had been switched on.

These results show the high potentialities of this carbonate aquifer highlighting limited drawdown when the pumping rate is maximum, even after 3 months pumping.

In conclusion, the pumping test has led to coherent results of hydrodynamic parameters despite the use of this method in atypical manner, using pumping wells for water exploitation for both monitoring and
realize the test.

**Declarations**

**Data availability**

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

The author(s) declare no competing interests.

**Author Contribution**

Conceptualization SR, DDC; Survey campaign and Data curation SR, DDC; Methodology SR, DDC, ADG; Software DDC, ADG; Supervision SR; Writing - original draft SR, ADG; Writing - review & editing ADG; all authors reviewed the manuscript

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**Figures**

**Figure 1**

Regional and local framework: (1) alluvial deposits of the main rivers and intramontane basin; (2) foredeep basin deposits; (3) turbiditic deposits; (4) carbonate deposits; (5) Tirino valley’s main springs; (6) Tirino river; (7) study area.
Figure 2

A. Geo-hydrogeological map (simplified APAT, 2005a): (1) Gravelly – sandy complex; (2) Gravelly – sandy and clayey complex; (3) Clayey and marly complex; (4) Gran Sasso Carbonate complex; (5) Direct fault; (6) Thrust; (7) Cross-section trace; (8) Well field area. B. Hydrogeological cross-section. C. Well field localization: (1) Well; (2) Equivalent well (EW); (3) Gravelly – sandy complex; (4) Gravelly – sandy and clayey complex; (4) Gran Sasso Carbonate complex; (6) Direct fault; (7) Cross-section trace; (8) Well field area. D. Detailed hydrogeological cross-section.
Figure 3

Pumping test scheme; the aquifer is approximated to a phreatic one in the steady state condition. (z stands for piezometer). All parameters refer to equations 2 and 3.
**Figure 4**

Example of step-drawdown test plots: Hydraulic head vs Time

**Figure 5**

Example of semilogarithmic plot “Depth from the ground vs Time” for Q = 740 l/s (third step).
Figure 6

Characteristic curves (Drawdown vs Pumping rate plot) for the monitored wells and piezometers (Pz).
Figure 7

Water table reconstruction in static conditions after recovery. (1) Well/Piezometer; (2) Equivalent Well (EW); (3) Well field area; (4) Main contour; (5) Auxiliary contour; (6) Flow direction.
Figure 8

Water table reconstruction in dynamic conditions after 5 days from test beginning. (1) Well/Piezometer; (2) Equivalent Well (EW); (3) Well field area; (4) Main contour; (5) Auxiliary contour; (6) Flow direction.