
Experiment of pumping at constant-head: an alternative possibility to the sustainable yield of a well

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Abstract The effects of constant-head pumping on a well over a period of 1 year have been monitored and the results used in the research of a potential alternative for the attainment of sustainable yield. Sustainable yield is frequently related to the response of drawdown during a pumping test at constant-rate, which sometimes involves a difficult choice of conceptual model to be used to analyse the pumping results. The experiment, carried out on a well that taps a fractured aquifer in Italy, recorded the aquifer's response to pumping, compared with the response of springs. From the trends in discharge variation with time, the period and magnitude of the recharge and the stored water volume at the beginning of the depletion period can be evaluated, and the discharge rate during the same depletion period can be predicted. A sustainable yield can be derived based on the water volume extracted during the depletion period rather than on the prediction of drawdown over a long time. The experiment also highlights the stability of water quality extracted from the well, and where this criterion is important, in some cases, the constant-head pumping can represent an alternative method of groundwater exploitation.

Résumé Les effets d'un pompage à charge constante sur un puits pendant une période de un an ont été surveillés et les résultats ont été utilisés pour la recherche d'une alternative potentielle à l'obtention d'un rendement durable. Ce dernier est fréquemment lié à la réponse du rabattement lors d'un essai de pompage à taux constant, ce qui implique parfois un choix difficile du modèle

conceptuel à utiliser pour analyser les résultats de l'essai. L'expérience, réalisée en Italie sur un puits exploitant un aquifère fracturé, consistait à enregistrer la réponse de l'aquifère au pompage et à la comparer à celles des sources. À partir des tendances observées de la variation du débit dans le temps, la période et l'importance de la recharge ainsi que le volume d'eau stocké au début de la période de rabattement peuvent être évalués; le débit peut être prédit pour cette même période. Un rendement constant peut être dérivé en se basant sur le volume d'eau extrait pendant la période de rabattement plutôt que sur la prévision du rabattement sur une longue durée. L'expérience met également en évidence la stabilité de la qualité de l'eau extraite du puits, et lorsque ce critère est important, dans certains cas, le pompage à charge constante peut représenter une méthode alternative d'exploitation des eaux souterraines.

Resumen Durante un periodo de un año, se ha monitorizado el efecto de un bombeo constante en un pozo y los resultados han sido utilizados para investigar una potencial alternativa para la consecución de un caudal sostenible. El caudal sostenible está relacionado frecuentemente con la respuesta del descenso durante un ensayo de bombeo con un caudal constante, lo que a veces implica una difícil selección del modelo conceptual que se debe utilizar para interpretar los resultados del bombeo. El experimento, llevado a cabo en un pozo que explota un acuífero fracturado en Italia, registró la respuesta del acuífero al bombeo, comparada con la respuesta de manantiales. A partir de las tendencias de la variación de la descarga con el tiempo, puede evaluarse el periodo y la cantidad de la recarga y el volumen de agua almacenado al principio del periodo de vaciado, y se puede predecir el rango de la descarga durante el mismo periodo de extracción. Se puede obtener un caudal sostenible basado en el volumen de agua extraído durante el periodo de agotamiento más que en la predicción del descenso durante un largo tiempo. El experimento también arrojó luz sobre la estabilidad de la calidad del agua extraída del pozo, y en algunos casos donde ese criterio es importante, el bombeo a nivel constante puede representar un método alternativo para la explotación de aguas subterráneas.

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Introduction

The determination of the sustainable yield of a well falls within the widest scope of groundwater management. One has to consider that withdrawals from wells necessarily modify the natural hydrologic cycle, by increasing the recharge or by diminishing the natural discharge or the aquifer's storage, or through a combination of these factors (Domenico and Schwartz 1990). The challenge is to regulate the withdrawals with reference to the aquifer conditions considering also the ecological, economic and legal impacts of pumping (Barlow et al. 2004). The breadth of the topic is supported by the literature, starting from the established concept of "safe yield" (Lee 1915; Meinzer 1923; Conkling 1946; Banks 1953) and has been subsequently developed to incorporate scale such as the scale of a single well, an aquifer or a groundwater basin (for example, Bear and Levin 1967; Domenico et al. 1968; Freeze 1971; Domenico 1972; Bredehoeft 1997, 2002; Sophocleous 1997; Wood 2001; Alley and Leake 2004; Kalf and Woolley 2005).

When the task is simply to analyse the impact of withdrawal from a single well, the tendency is to analyse the "sustainable yield" of a well (for example, Murray and Sami 1998; van Tonder et al. 2001). This quantity is defined as the discharge rate that will not cause the water level in the well to drop below a prescribed limit, identified from the nature and thickness of the aquifer and the depth of the well. Then, the sustainable yield (Q_{sus}) can be determined, for example, through the following expression (van Tonder et al. 2001):

$$Q_{\text{sus}} = Q_{\text{ob}} \frac{s_p}{s_{\text{ob}}(t')} \quad (1)$$

where s_p is the drawdown of the well corresponding to the prescribed limit and $s_{\text{ob}}(t')$ is the drawdown at the time t' observed in the well during a test with a constant discharge rate Q_{ob} ; t' represents the time in which the drawdown does not exceed the prescribed limit. The application of Eq. (1) needs the knowledge of relation $s_{\text{ob}}(t')$ over a long period. The expression for drawdown over a long period is generally extrapolated from pumping tests restricted to a few days and this presents difficulty in the calculation of the sustainable yield, especially where the aquifer system is very heterogeneous. Another point that affects the prediction of drawdown over a long time is the rate at which the aquifer can be recharged by precipitation. Nowadays, the approach adopted to establish the yields of production wells, especially from heterogeneous aquifers or low permeability rocks, involves processing data arising from the response to pumping at constant rate and to adopt a method of interpretation from a more or less complex range of tests (Murray and Sami 1998; van Tonder et al. 2001).

This paper reports on the results of a constant-head pumping test carried out for about 1 year on a well that penetrates carbonate rocks in southern Italy. The objective

of the experiment is to investigate an alternative solution to the determination of sustainable pumping rates when, having a limited knowledge of an aquifer, one wishes to effect a minimum, controllable impact on the aquifer. At the same time, the experiment aims to verify which aquifer characteristics can be deduced from its response to the discharge rate of the well over a long time, including the effect on aquifer recharge.

Pumping experiment procedure

When the flow characteristics, hydraulic parameters and recharge rate of an aquifer are not sufficiently known, the practical application of Eq. (1) to determine the sustainable yield of a well (Q_{sus}) can render the equation ineffective. Difficulties can occur when the aquifer response to drawdown is only observable for the pumped well for a short period. Pumping to attain constant-head for a prolonged period, a year or more, can be an alternative, temporary method of well production. At the same time, the pumping experiment allows precious elements of local hydrogeological characteristics to be understood.

The suggested procedure includes the determination of a constant drawdown (s_w') based on the characteristics of the well (well depth, water-bearing formation intersected by the well, depth of submersible pump) and the analysis of a standard step-drawdown test or short constant-rate test. Subsequently, the procedure involves pumping at the determined constant drawdown (s_w') and monitoring the discharge rate of the well over time.

The data acquired during the constant-head pumping stage can be processed using the available methods associated with unsteady flow to a well (Jacob and Lohman 1952; Hantush 1959; Glover 1978; Mishra and Guyonnet 1992). The analysis of discharge variations as a function of time allows for the determination of certain aquifer parameters over a long period. These parameters can enable the application of the Eq. (1). The difficulties with this method of analysis relate to the determination of the effective radius of the pumping well which affects the calculated hydraulic parameters (Bear 1979).

An alternative method of interpretation of the pumping response at constant-head can be based on the theoretical comparison of the well discharge variations with those of spring flows during depletion. Even in this case, one must consider a constant drawdown, depending on the difference between the hydraulic head in the aquifer and the head imposed at the spring by the elevation of the point through which groundwater emerges at the ground surface.

Amongst the numerous solutions available for the depletion curves of springs (Maillet 1905; Drogue 1972; Mangin 1975), one solution underlines the exponential type of curve:

$$Q_{\text{sp}} = Q_{0\text{sp}} e^{-\alpha t} \quad (2)$$

where Q_{sp} is the spring's discharge at any time t from the beginning of depletion, Q_{0sp} is the discharge at the beginning of the depletion, α is a recession constant representing the aquifer's geometry (e.g. areal extent), transmissivity and storativity (Bear 1979).

The analogy between the depletion curve of springs and the decrease of the flow rate of a well pumped at constant-head, allows for calculation of the coefficient α and the water volume stored in the aquifer that feeds the well at the beginning of the depletion period (V_0). A value for V_0 allows for calibration of the abstracted volume, including also the effect of the recharge of the aquifer. This means that it is possible to determine the sustainable yield of a well based on the actual response of the discharge rate rather than on the prediction of drawdown over a long time.

Description of the experiment and results

The well is situated at the foot of the eastern slopes of the Alburni Mountains, a carbonate massif approximately 120 km to the SE of Naples (Fig. 1). The Alburni Mountains form one of the most extensive karstic areas (approximately 200 km²) of southern Italy (Brancaccio et al. 1973; Santangelo and Santo 1997).

The relief is due to a very thick succession of Mesozoic platform carbonates (thousands of metres), consisting of Lower Liassic–Upper Triassic dolostones at the base, a considerable thickness of limestones (Upper Cretaceous–Middle Liassic) and a reduced thickness of limestones and marls (Lower Eocene–Paleocene; Bonardi et al. 1988).

These carbonate mountains give rise to a hydrogeological system characterized by a very complicated groundwater circulation system due to the articulated structural situation and the development of a network of karstic conduits. A potential yield of about 240×10^6 m³/year has been estimated for this hydrogeological system, discharging primarily towards the springs situated at the base of the massif (approximately 3.6 m³/s) and increasing the streamflow of the lower Tanagro River (approximately 4.0 m³/s). Considering the location of the main springs and branches of gaining rivers (Fig. 1), it was deduced that the directions of groundwater flow are mainly oriented NW (Celico 1978, 1983; Celico et al. 1994).

The well was located on the eastern margin of the hydrogeological system in the Vallo di Diano plain (Fig. 1), a morpho-structural depression where the carbonate rocks are lowered and covered by Miocene flysch and Quaternary detritic, alluvial and lacustrine deposits. In this area, one does not foresee groundwater exchanges between the Quaternary aquifer of the plain and the carbonate aquifer (Nicotera and de Riso 1969; Celico 1983). Further north, wells drilled at the base of the carbonate relief revealed a considerable variation in the aquifer's transmissivity (from 10^{-1} to 10^{-4} m²/s), due to the notable hydraulic heterogeneity of the fractured rocks, also tied in with the development of the karstic conduit system (Celico 1991; Bolognini et al. 1994).

The well was percussion drilled to a depth of 162 m bgl (meters below ground level). The carbonate aquifer was encountered at 79 m, below predominantly clayey, detritic and lacustrine deposits (Pleistocene–Holocene) and Miocene flysch (Fig. 2). The aquifer is formed by Cretaceous limestone with a variable degree of fracturing. Formation samples taken at different depths showed that the discontinuities of limestone are often filled with fine sediments or calcite deposits. No enlargement of joints and fractures due to secondary solution of carbonate rock have been observed.

The water level stabilized at around 64 m depth, therefore, the carbonate aquifer is to be considered confined. The well was completed with a 30 m long, 1.75 mm aperture Johnson screen as shown in Fig. 2 so as to capture the main water entries from the more fractured layers of the limestone.

The first step-drawdown test was carried out for an overall time period of 18 h with a variable discharge rate between 1.4×10^{-3} and 6.5×10^{-3} m³/s. The discharge (Q)–drawdown (s_w) curve of the well (Fig. 3) was drawn using the drawdown recorded at the end of each discharge step (3 h for each step); a good fit to Jacob's (1947) model was confirmed for the relationship between drawdown and discharge rate, according to the following expression:

$$s_w = 4.84 \times 10^3 Q + 6.95 \times 10^5 Q^2 \quad (3)$$

with s_w expressed in metres and Q in m³/s.

A further test was carried out at a constant rate of 7.6×10^{-3} m³/s, measuring the drawdown in the well as a function of time, as reported in Fig. 4. From the graph, it can be seen that there is a good fit of the relationship drawdown (s_w)–time (t) to the Cooper-Jacob straight-line model (Cooper and Jacob 1946) up to around 100 min. One also sees a second segment on the semilog s_w – t graph with a lower slope, probably due to the aquifer's heterogeneity. The two segments on the graphs are described by the following equations:

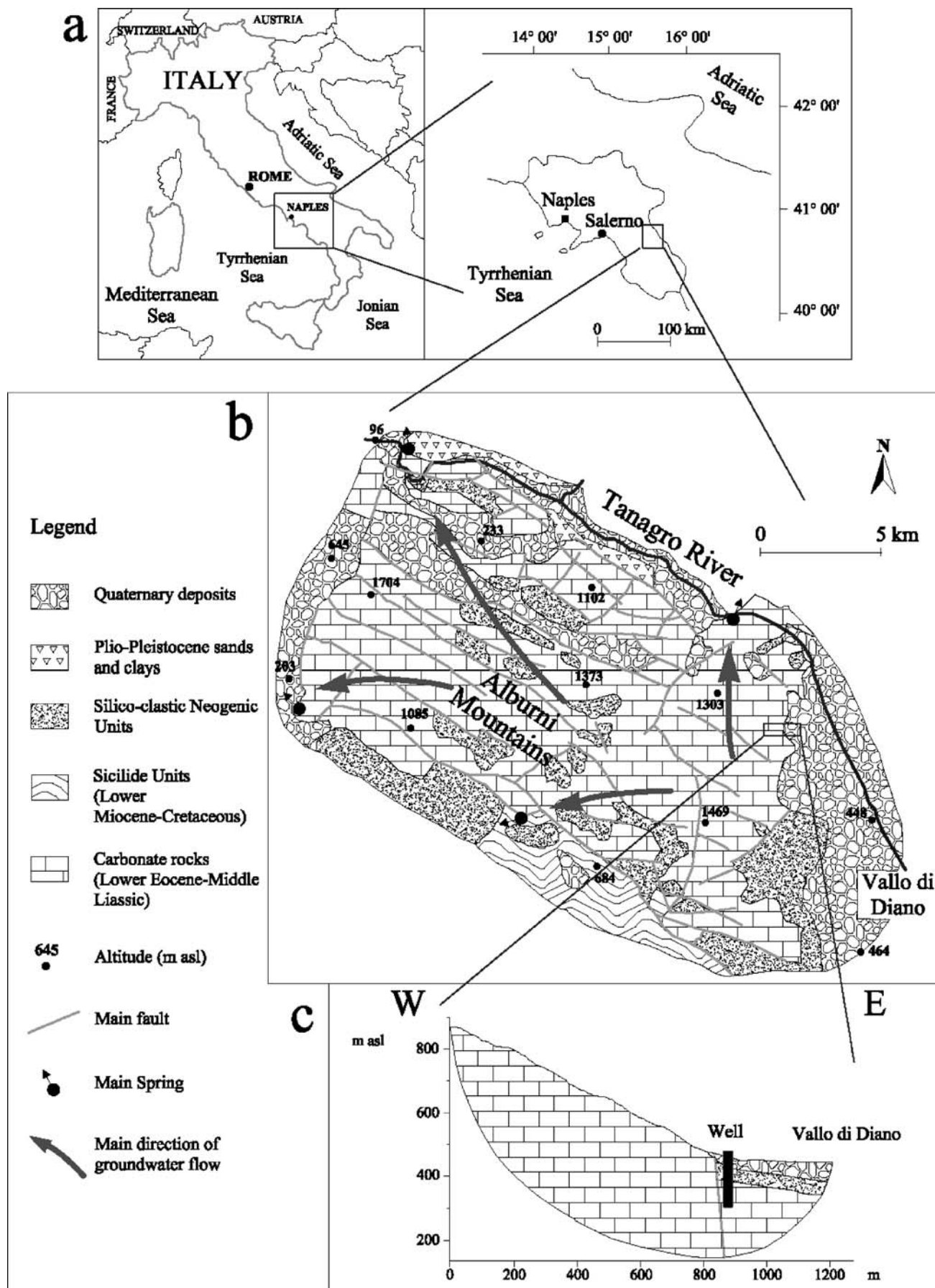
$$s_w = 13.90 \ln t + 13.06 \quad \text{for } t < 90 \text{ min} \quad (4)$$

$$s_w = 2.97 \ln t + 60.98 \quad \text{for } 100 < t < 240 \text{ min} \quad (5)$$

with s_w expressed in metres and t in min.

Applying the Cooper-Jacob method to the segments of the graph of Fig. 4 (excluding the first minutes of pumping, under the influence of the well's storage), one calculates rough values of transmissivity between 4×10^{-5} m²/s and 2×10^{-4} m²/s.

Based on the results of the tests performed, the constant drawdown for the functioning of the well was defined. From Eq. (3), it was calculated that for a drawdown s_w' of around 12 m, the well efficiency is greater than 75%. This drawdown is equivalent to around 18% of the available drawdown of the well, calculated as



◀ **Fig. 1** **a** Location of the study area with **b** general geologic outline. **c** Cross-section of the well location (well depth=162 m below ground level)

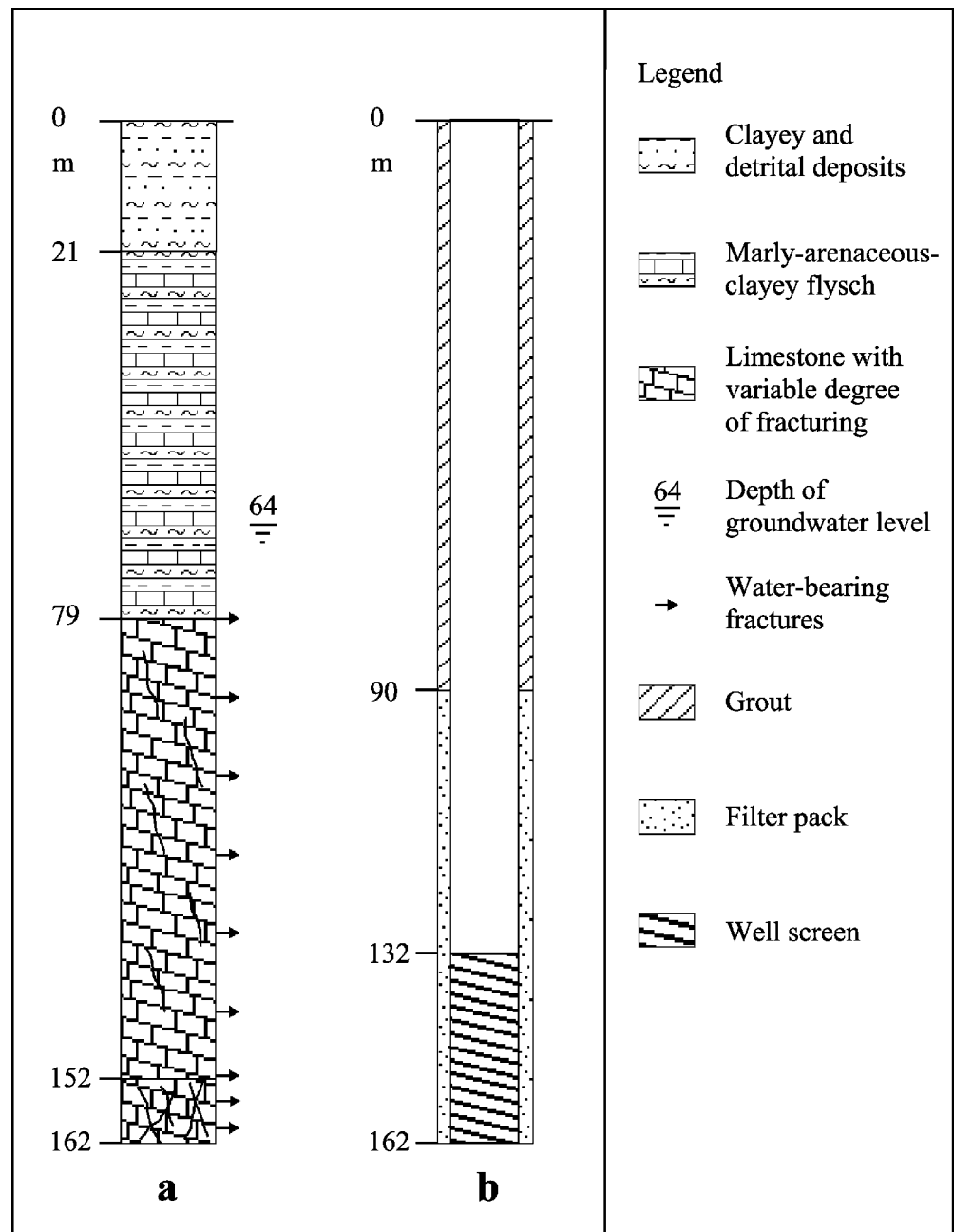
being the difference between the depth of the static level and that of the top of the screen. Therefore, with this drawdown, one should have an essentially laminar flow, considering also the low transmissivity.

Subsequently, the well was equipped with a 30 kW submersible electric pump. An electromagnetic flow meter and a multiparameter probe for the measurement of level, electrical conductivity, pH and temperature were also installed (Fig. 5). The data measured at 1 min intervals by both instruments were registered on a digital

recorder. The submerged electric pump is controlled by a variable frequency drive which, following suitable modifications, permits the well to operate at a constant head.

Figure 6 illustrates the well's discharge rate trend during the period between March 2004 and April 2005. In spite of some irregularities in the level due to technical reasons (maintenance, electric power cuts, temporary deactivation of the monitoring instrumentation, etc.), one can see a general trend in the discharge rate related to the local precipitation regime, allowing for an aquifer response time of some months. In fact, the rainfall that occurred from September to November 2004 influenced the discharge rate only at the end of December 2004.

Fig. 2 **a** Stratigraphy and **b** well design



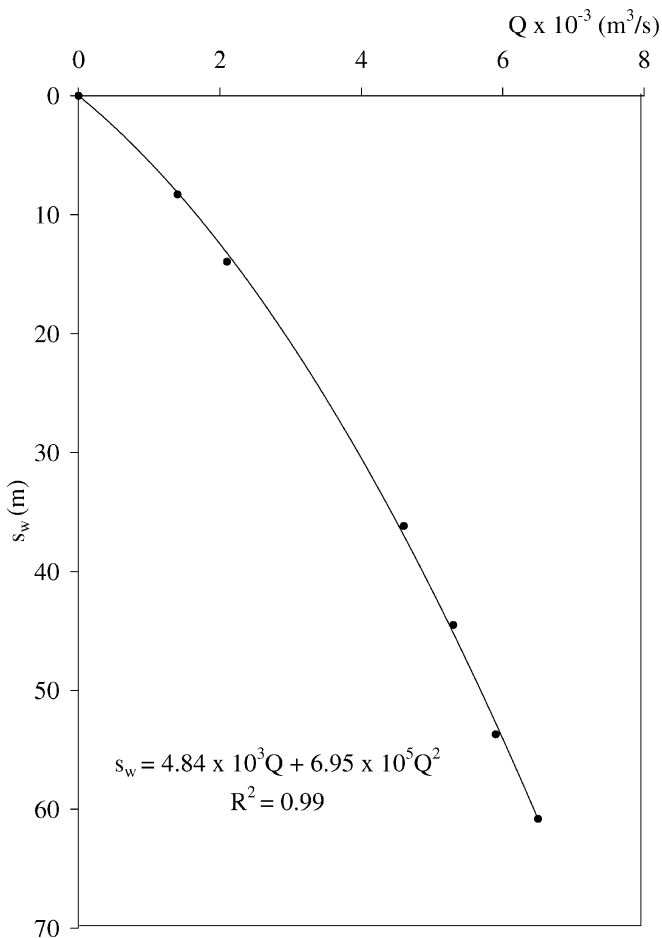


Fig. 3 Discharge (Q)–drawdown (s_w) plot from the step-drawdown test, drawn using the drawdown recorded at the end of each discharge step (3 h for each step)

From the graph of Fig. 6, the discharge depletion period between 28 July and 8 November 2004 was extrapolated and analysed in detail. This section shows a variation of discharge rate from 3.18×10^{-3} to 2.19×10^{-3} m³/s, a constant drawdown ($s_w' = 12$ m), and few technical disturbances, uninfluenced by recharge.

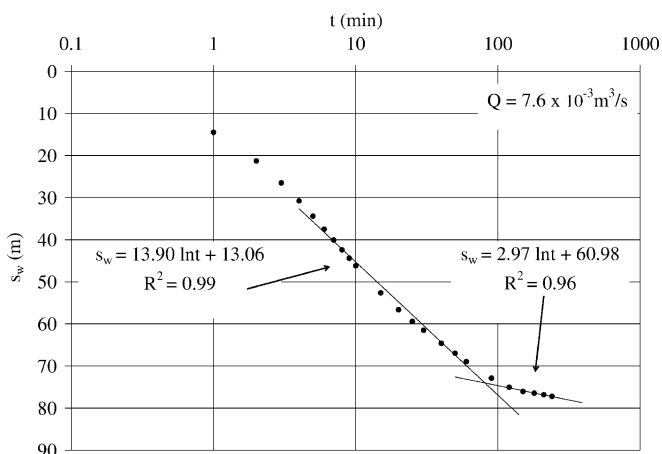


Fig. 4 Time (t)–drawdown (s_w) plot from the constant-rate pumping test

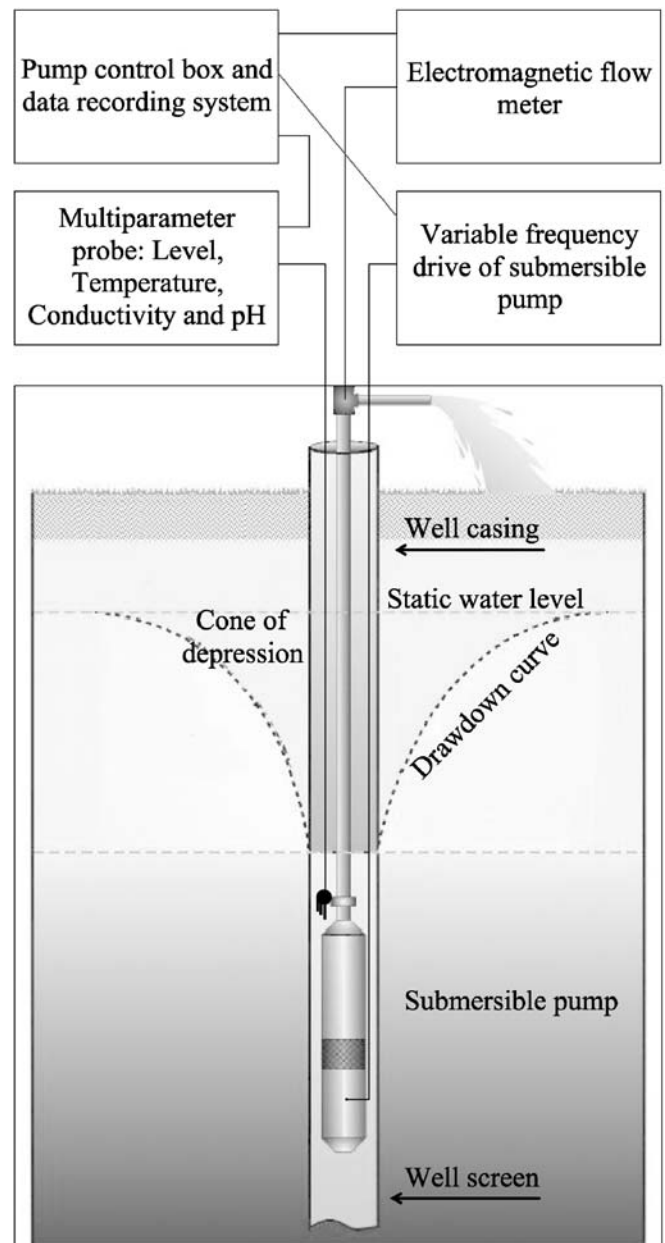


Fig. 5 Diagram illustrating the well equipment

The trend of the Q – t expression was compared with those defined for unsteady flow to a flowing well (Jacob and Lohman 1952) and for depletion curves of springs. From this comparison it appears that the whole curve is better suited to the decrease trends of springs than to those indicative of flowing wells. In particular, one finds a considerable adaptation between the expression Q – t for the well (Fig. 7) to that of Eq. (2):

$$Q = 3.18 \times 10^{-3} e^{-0.0036t} \quad (6)$$

with t expressed in days and Q in m³/s.

From the previous Eq. (6) can be calculated, for the period in question, a water volume stored in the aquifer which feeds the well at the beginning of the depletion (V_0)

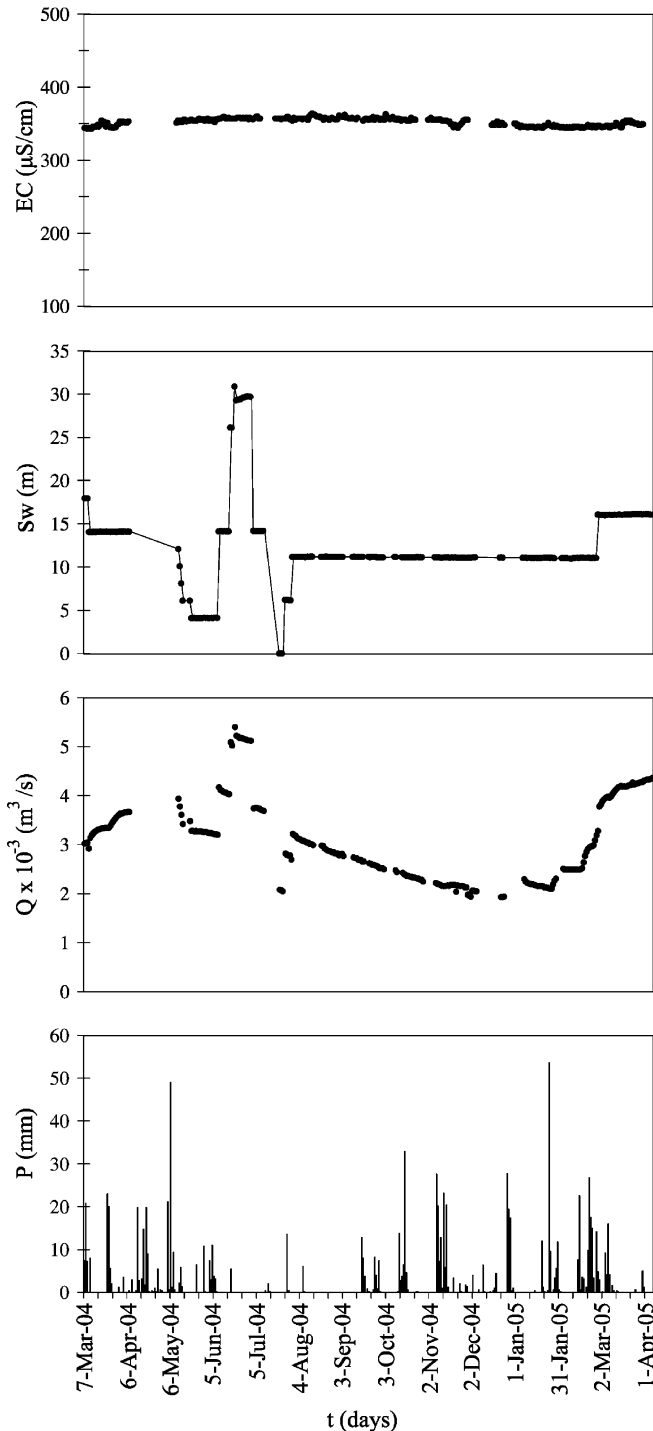


Fig. 6 Variation in precipitation (P), well discharge (Q), drawdown (s_w) and electrical conductivity (EC) during tested time

of some $76.3 \times 10^3 \text{ m}^3$, the volume extracted from the well in the 104 days of pumping (ΔV) of around $23.8 \times 10^3 \text{ m}^3$ and, therefore, a percentage of the emptying volume ($\Delta V / V_0 \times 100$) of around 31%.

The expression $Q-t$ shows the poorest fit to the Jacob and Lohman model (Fig. 8). For the first 13 days of the examined period, it seems to follow the tendencies indicated by the model, but then the discharge decrease

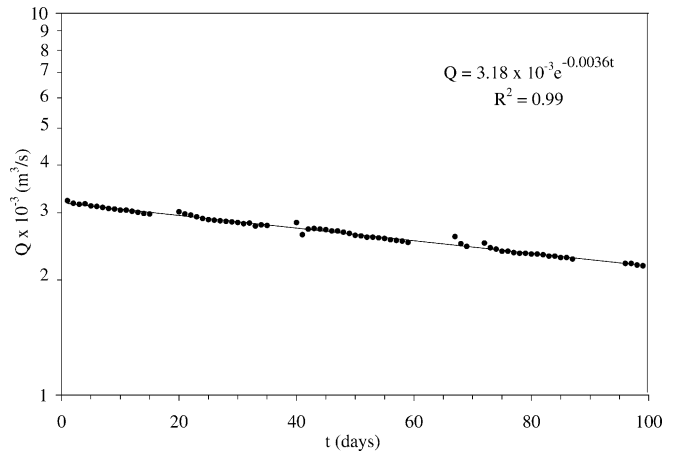


Fig. 7 Time (t)–well discharge (Q) plot during depletion period (the daily average data are plotted)

is faster than that for the previous segment. This discrepancy with the model of Jacob and Lohman can be explained as being due to the heterogeneity of the aquifer, as was observed previously during the constant pumping-rate test. The electrical conductivity of the water did not significantly change during the experiment, as one can see from the graphs of Fig. 6.

Discussion

The results of this experiment demonstrate that constant-head pumping highlights a trend for the discharge rate extracted from the well that is very similar to the springs' hydrogram. Therefore, through the analysis of the decline trend of the well discharge one can define the period and amount of the recharge, evaluate the water volume stored in the aquifer which feeds the well at the beginning of depletion and modulate the percentage emptying of the volume stored. These factors permit minimization of the impact of extraction on the aquifer's local yield controlling the constant-head as a function of the hydrogeological parameters and of the thickness of the available saturated aquifer. Furthermore, it is possible to calibrate the withdrawal during depletion periods as a function of the annual variations of the recharge, evaluating the water volume stored by the aquifer at the beginning of the depletion.

The variation of the discharge rate of the well during the depletion period can be used to determine a value of the sustainable yield. Referring to the experiment results for a constant drawdown (s_w') of 12 m, in 104 days of pumping, the discharge rate changed from 3.18×10^{-3} to $2.19 \times 10^{-3} \text{ m}^3/\text{s}$. During this period, a percentage of the water volume of 31% had been pumped from volume stored by the aquifer at the beginning of the depletion considered. If this emptying percentage of the aquifer is considered sustainable, then the volume extracted from the well in the 104 days of pumping (ΔV) results in about $23.8 \times 10^3 \text{ m}^3$ which can be obtained with an average constant rate (Q_{ac}) of $2.65 \times 10^{-3} \text{ m}^3/\text{s}$. This Q_{ac} differs from the value (Q_{sus}) computable through the results of the

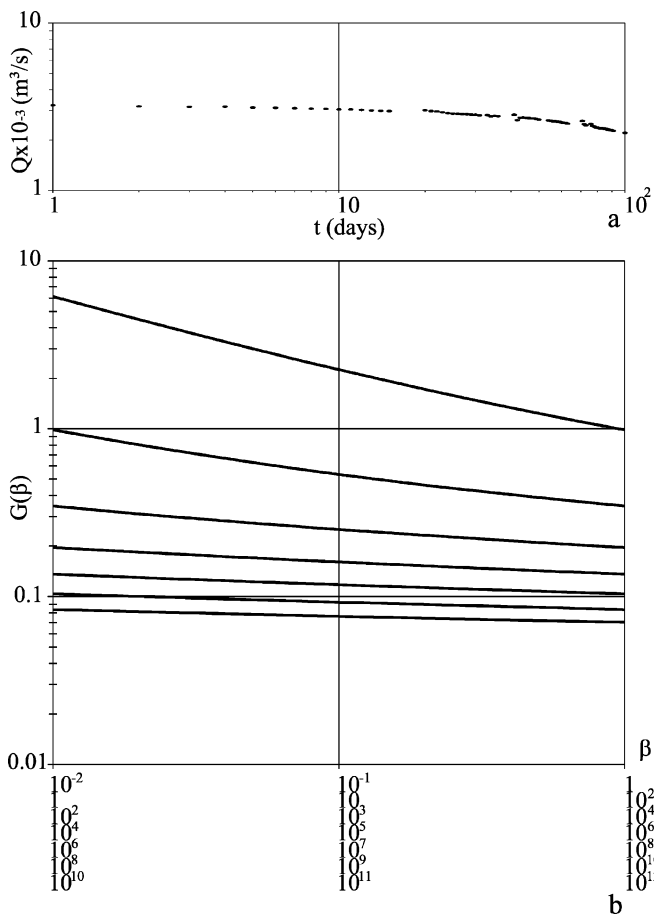


Fig. 8 a Log-log plot of time (t)–well discharge (Q) during depletion period compared with b the well function $G(\beta)$ of Jacob and Lohman (1952) for the flowing well

short duration constant-rate test and the application of Eq. (1). In fact, Eq. (5) results in a drawdown (s_{ob}) of 96 m for $t' = 104$ days and $Q_{ob} = 7.6 \times 10^{-3} \text{ m}^3/\text{s}$. From these data, and considering $s_p = s_w' = 12 \text{ m}$, a value of $Q_{sus} = 0.94 \times 10^{-3} \text{ m}^3/\text{s}$ results.

The sustainable yield of the well computed from the previous analysis of a constant-head pumping test has annual significance, being influenced by the recharge proceeding the depletion period. Therefore, a different value of sustainable yield for each year would be considered. The observation of more years of constant-head functioning of a well could be a method to test the pumping regime and to determine an appropriate Q_{ac} for the following years, having more values of discharge (Q_0), of coefficient α and relative rainfall rate at disposal.

In some cases the constant-head pumping can be an alternative method of management of the well. One case is the pumping of mineral or thermal waters when a qualitative stability of the waters extracted from a well must be ensured. With a constant-head, it is the pumping flow rate that adapts itself to the hydrologic cycle, maintaining the storage depletion of the aquifer within controlled values. This also implies a qualitative stability of the waters extracted, as shown in the complete stability

in the electrical conductivity measured during the experiment. This pumping style safeguards not only the hydrogeological equilibrium but also the life of the well. In fact, a well operating at constant-head, which does not permit dewatering to take place, avoids air being sucked in by the pump and, in reducing turbulent flow, protects the screen from deterioration.

Another case is the tapping of a spring when there are existing environmental restrictions: for example, in relation to the instream flow requirements for fish and wildlife, or where there are significant ecosystems influenced by the spring that are incompatible with groundwater exploitation activities. In such cases, a constant-head well, suitably located, would permit the withdrawal of only a part of the flow feeding the spring and at the same rate with which waters feeding the spring are replenished by recharge, leaving the necessary residual discharge available to a surface flow useful to the sustainability of the ecosystems connected with it. At the same time, because of the effects induced by a greater unsaturated zone associated with the aquifer that supplies the well, groundwater extraction using the well would ensure a greater protection of the resources exploited. Furthermore, the residual flow rate discharged by the spring over time would constitute a real monitoring system for the impact of such exploitation on the aquifer system being tapped. Finally, if one refers to what was previously suggested concerning the effect of exploitation of groundwater (Domenico and Schwartz 1990), the withdrawal from a well at constant-head, as an alternative to the direct exploitation at the spring, can represent an elastic and dynamic method for reaching a good compromise between increasing recharge and reduction of the natural discharge of the aquifer with direct control on the reduction of the aquifer's storage.

Conclusions

The experiment carried out, having a well pumped at constant-head for about 1 year, and therefore, at a variable discharge rate, has shown that:

- The discharge rate trend with time is similar to that of the springs' hydrograms
- The water volume extracted does not exceed the recharge
- Waters extracted have shown a substantial qualitative stability

These characteristics, together with the consideration concerning the reduced transmissivity of the aquifer tested, permit one to deduce that the pumping at constant-head can represent, in some cases, an alternative in the range of techniques available for groundwater exploitation. This alternative is particularly advantageous when it is necessary to limit the drawdown of the well and aquifer, or when faced with limited hydrogeological information on the setting around the well. In such cases,

especially for continuous pumping through time, using this technique one has a controllable impact on the exploitation of the aquifer and at the same time the opportunity to adapt the pumping rate in accordance with local hydrogeological characteristics and to vary the annual recharge rate. When a constant rate is requested, a temporary pumping exercise at constant-head allows for the determination of a sustainable yield, taking into consideration the average discharge rate based on the water volume extracted during the depletion period analysed.

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