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Modeling the hydraulical behavior of a fissured-karstic aquifer in exploitation conditions

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Abstract

A 5-year daily measurement of the dynamic level in a borehole was plotted versus cumulative yield since the beginning of exploitation. Eighty percent of the experimental curve is explained by a linear function ($h = aQ_c + h_0$) by intervals. Only floods, which follow heavy storms and non-pumping cannot be taken into account. The slopes of the straight lines are spread around two constant values of the slope: $a_r = +0.35 \times 10^{-3}$ m m^{-3}, which characterizes the part which is controlled by recharge, and $a_p = -0.14 \times 10^{-3}$ m m^{-3}, which characterizes the draining part of the aquifer fractures. This linear fitting demonstrates that the borehole–aquifer system can be considered as an equivalent continuous medium, where the linear relationship between dynamic head and pumped yield are defined by the values of a_r and a_p. Thus the hydraulic behavior of the aquifer differs according to the pumping rate: equivalent continuous medium for a low rate, dual permeability for a high one. This work demonstrates that the long-term behavior of an exploited fissured aquifer can be described by a simple model, if the duration of the aquifer test is long enough (1–3 months). It also shows that the production phase must include repetitive head measurements in order to refine the exploitation yield and the management conditions. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Aquifer test; Discontinuous medium; Karst; Exploitation borehole

1. Introduction

Determining the influence area of a production well in a fissured and karstified medium constitutes one of the most difficult problems in hydrogeological studies, because of the high heterogeneity of the reservoir and the complexity of water flow.

Two approaches are often used. The probabilistic approach uses the characteristic features of the fissured media (geometry and spatial distribution of fissures) to compare the different domains of the aquifer. Geostatistical and fractal methods are applied to evaluate the variations of the fissured medium (Matheron, 1963; Bangoy, 1992; Gondo, 1996).

The deterministic approach is based on the study of the hydraulic behavior of the matrix and fissure zones. It is based on the analysis of physical indications of exploitation, pumping yield and piezometric variations (Bruel et al., 1999). Thiery et al. (1983) compares the behavior of the fissured medium to that of an equivalent porous medium based on linearity of flux and head gradient. Other authors compare the fissured medium to a double porosity medium

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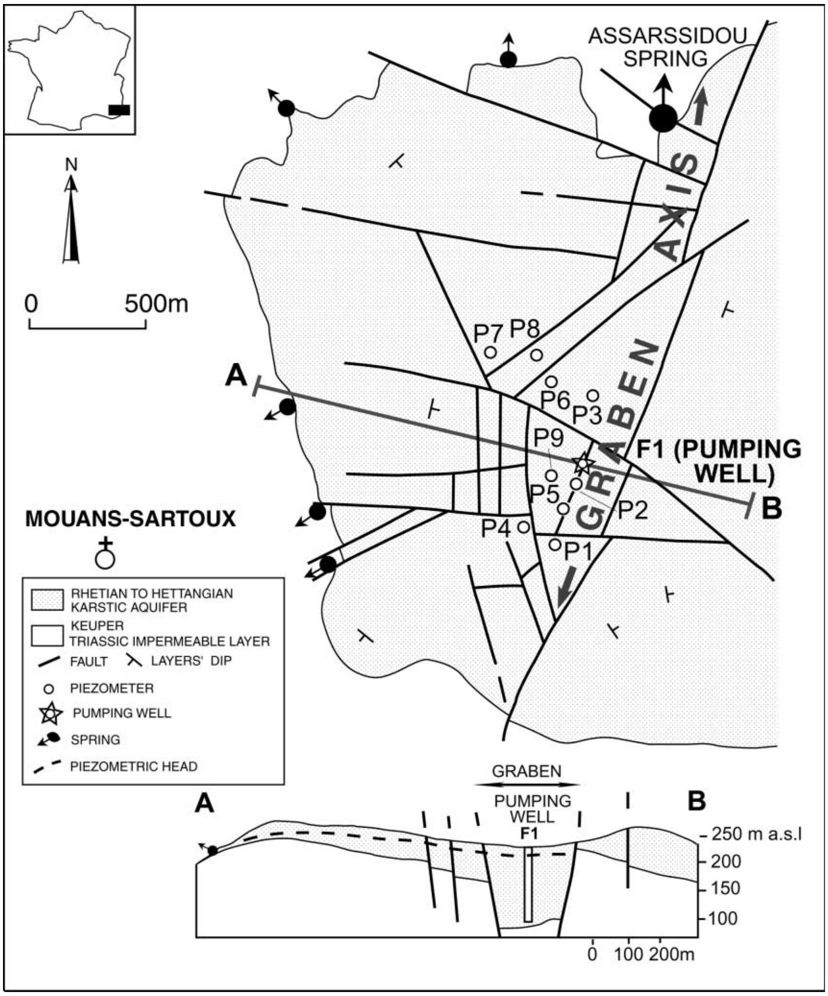


Fig. 1. Hydrogeological map and cross-section of the Pinchinade pumping area (Mouans-Sartoux).

(Bibby, 1981; Moench, 1984), where they demonstrate the binary effect of the low permeable system (low permeability matrix) and of the high conductivity drains (Drogue, 1980; Collignon, 1986; Mangin, 1994). All these approaches are based on a good knowledge of the medium, particularly on a high number of hydraulic conductivity measurements versus time and space. Therefore, many aquifer tests need to be performed in several boreholes, well dispersed in different areas of the reservoir. Such tests are rarely carried out because of the cost and variability of parameters in fissured media.

The problem is often reduced to the study of the aquifer reactions in a single pumping borehole, considering that the exploited aquifer reaches the limits of the reservoir. This is the case of our study, which is supported by a 5-year daily monitoring of drawdown in a continuously exploited borehole. This long record, which includes monitoring of pumped yields and rainfall episodes at the same time step, enables a characterization of the behavior of the borehole-fissured aquifer system under pumping conditions by means of a limited number of parameters. The results of this approach will be useful to elaborate long-term management scenarios of the water resource.

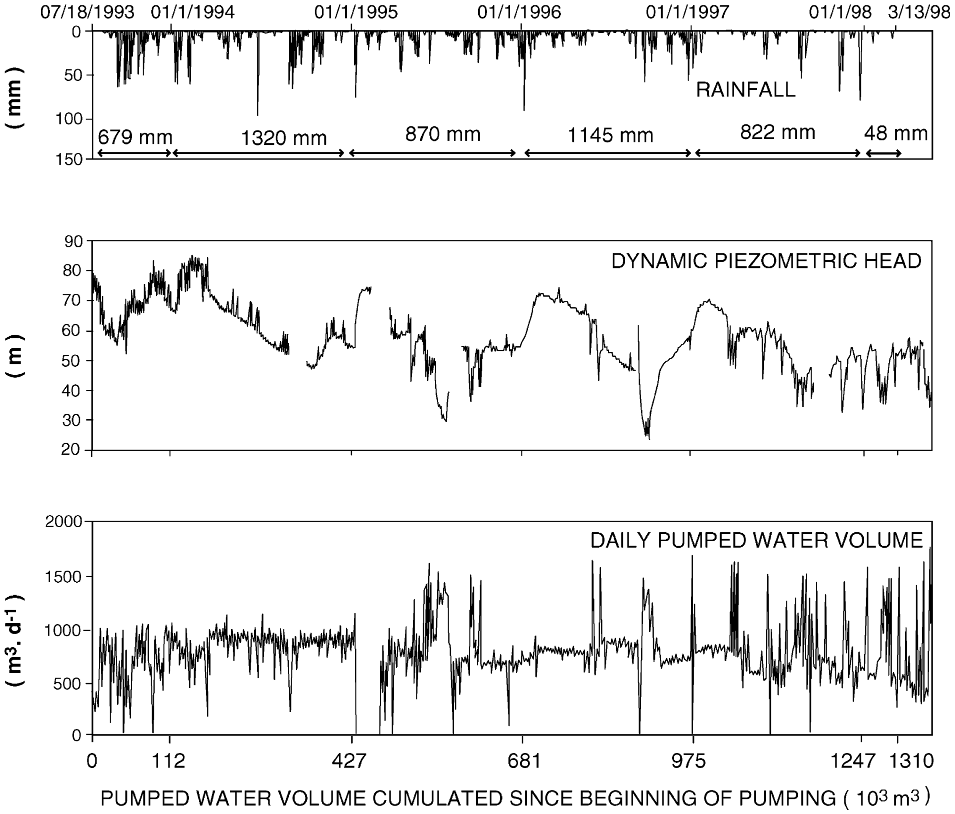


Fig. 2. Evolution of the dynamic level in borehole F1 compared to rainfall and pumped yield period 7/18/1993 to 2/22/1998.

2. Context of the aquifer exploitation

2.1. Hydrogeological context

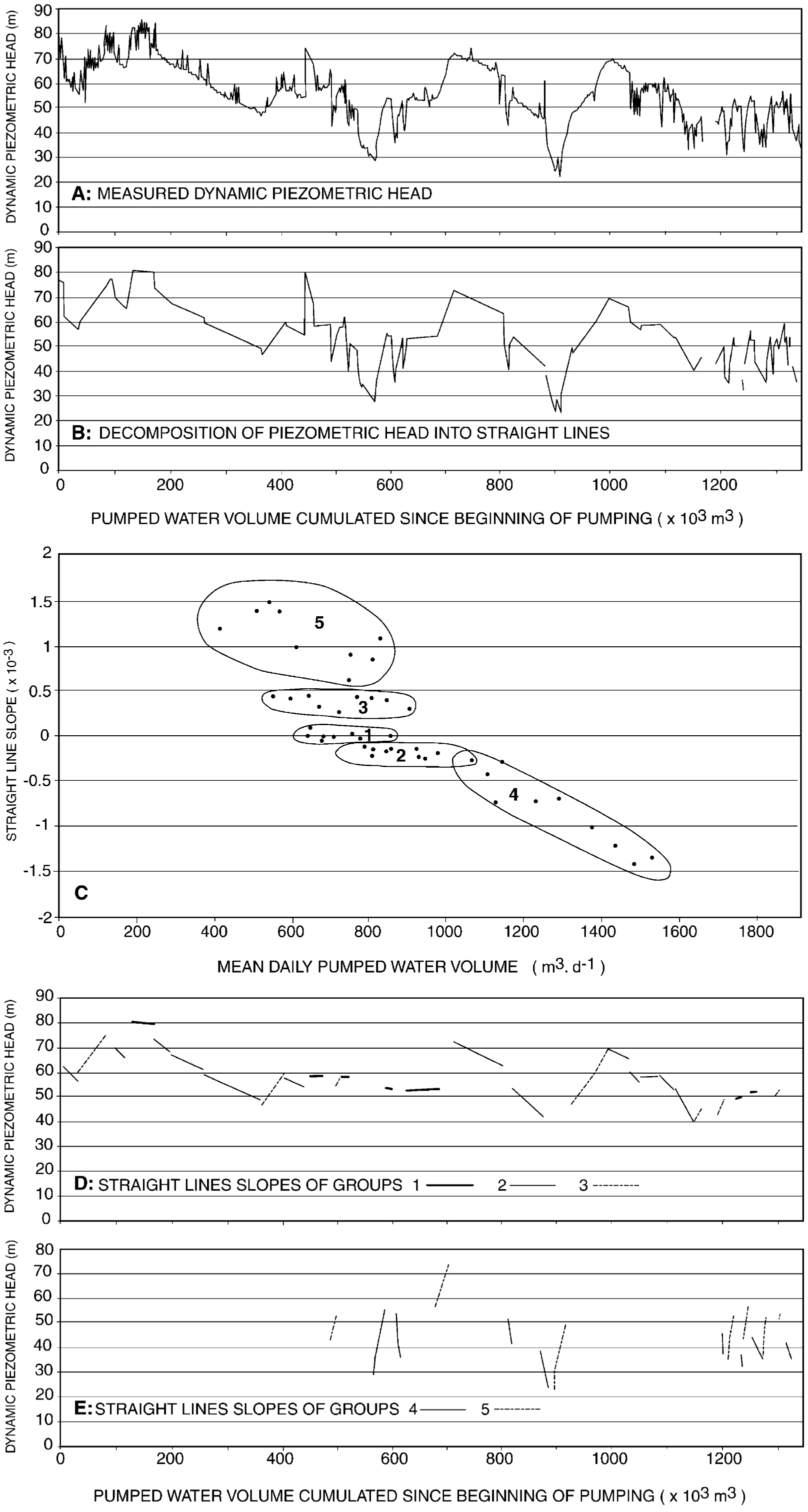
In the village of Mouans-Sartoux (Southeastern France), the pumping station is located in the Pinchinade graben, which is situated in the depth of a Rhetian to Hettangian limestone plateau (Fig. 1). The limestone outcrops on a 1 km^2 surface: 0.25 km^2 in the graben and 0.75 km^2 in the reminder of the plateau which is connected to the borehole by a fault network (Mangan, 1982, fig. 1). The karstified limestone is nested in dolomitic, clayey and gypsiferous formations, which can be considered as impervious at a regional scale (Fig. 1, cross-section AB).

The system is naturally drained by a spring which is situated on the northern edge of the plateau, at the topographically lowest point of contact with the impermeable Triassic formation (Assarssidou spring). Other smaller springs mark this contact on the western rim, but they have very low discharge throughout the year.

The well F1 is situated within the graben, which is the major drainage axis of the waters of the plateau (Guglielmi et al., 1997; Reynaud et al., 1998). Locally, inflows can occur through the Keuper basement, favored by the intensely fractured graben geometry, and by the presence of dolomite and gypsum lenses within the Keuper.

2.2. Exploitation conditions

The aquifer is exploited by a continuous pumping of about 800 $m^3\ d^{-1}$ in a 115 m deep borehole (Fig. 1, borehole F1). The pumping influence is strongly observed in the P2 and P5 piezometers, drilled in a fault area which is directly connected to the borehole (drawdawn of about 25 m), and more moderately on piezometers P3, P4, P6, P7, P8 and P9, which are situated in a less transmissive limestone block, or


DYNAMIC PIEZOMETRIC HEAD (m)
A: MEASURED DYNAMIC PIEZOMETRIC HEAD
B: DECOMPOSITION OF PIEZOMETRIC HEAD INTO STRAIGHT LINES
PUMPED WATER VOLUME CUMULATED SINCE BEGINNING OF PUMPING (x 10³ m³)
0 200 400 600 800 1000 1200
0 10 20 30 40 50 60 70 80 90
STRAIGHT LINE SLOPE (x 10⁻³)
C
1
2
3
4
5
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
0 200 400 600 800 1000 1200 1400 1600 1800
MEAN DAILY PUMPED WATER VOLUME (m³. d⁻¹)
D: STRAIGHT LINES SLOPES OF GROUPS 1 2 3
E: STRAIGHT LINES SLOPES OF GROUPS 4 5
0 10 20 30 40 50 60 70 80

less connected to the borehole, with a drawdawn of 2–3 m. Pumping influence is observed in all the springs of the area. It is low in the Assarssidou spring (10% reduction in flows), and it is more significant in the western springs of the site (drying up or major reduction of discharge). The reservoir is recharged by a $0.28 \times 10^6\ \mathrm{m}^3$ annual volume which corresponds to the average volume of local infiltration. This rough evaluation corresponds to the pumping volume during 1 water-year. This volume is measured between two dates when the head has the same value. The yearly yielded volume has the same order of magnitude as the recharge. Pumping yield, hydraulic head in the borehole and rain value are monitored daily.

2.3. Piezometric evolution of the exploitation borehole

The dynamic level versus time curve displays two main types of variations (Fig. 2):

Rapid variations (1–14 *d*), *during the 5-years monitoring period*. These variations correspond either to a lowering of the dynamic level, associated with a daily increase of pumping (drawdown ranging from 10 to 20 m for several hours) or to a rising of the dynamic level, following heavy rainfall episodes (for example, rising about 20 m in 14 d during a 200 mm rainfall episode, between 1/8 and 1/21/1994). These rapid variations are only measured in piezometers P2 and P5, which are directly connected the very conductive fissure network near the borehole.

Long term gradual variations (120–190 *d*). These variations correspond either to a slow lowering of the dynamic level during a period which is not influenced by rainfall (6/21–10/21/1994 or 2/16–8/31/1996 for instance), or to a progressive rising following an average intensity rainy period (20–30 $\mathrm{mm\ d}^{-1}$) of long duration (for example, 50 rainy days from 10/22 to 12/8/1994 or 63 d from 11/2/1996 to 1/3/1997). These gradual variations are observed simultaneously in all piezometers and springs indicating a wide lateral extension within the aquifer.

3. Separation of the relationship head versus cumulative pumped volume

In order to avoid infrequent pumping stop effects (the longest lasted 52 d between 1/18 and 3/9/1995), we expressed head variation in the borehole versus cumulative pumped volume since the beginning of exploitation (Fig. 3A). The curve is separated by intervals into a linear function. The straight segments, with a variable length (Fig. 3B), can be represented by a general equation

$$h = aQ_\mathrm{c} + h_0,$$

where h is the water head in the borehole; a the slope of the segment; h_0 the water head in the borehole at the lowest limit of the interval and Q_c is the cumulative pumped yield.

The slopes of the segments are plotted versus an average pumped volume (Fig. 3C). The positive slopes indicate a rising groundwater level. The negative slopes correspond to a lowering of groundwater level, due to pumping. The slopes are divided into five groups of values. Groups 1, 2 and 3 are composed of constant slopes, with average values of -0.14×10^{-3} to $+0.35 \times 10^{-3}$. These three groups represent 80% of the experimental curve (Fig. 3D). These slopes correspond to a 500–1100 $\mathrm{m}^3\ \mathrm{d}^{-1}$ pumping. A null slope is observed when the pumped yield balances the reservoir recharge. This ranges from 600 to 800 $\mathrm{m}^3\ \mathrm{d}^{-1}$. A negative slope indicates a slow and constant exhaustion of the reservoir, for pumped yields ranging from 800 to 1100 $\mathrm{m}^3\ \mathrm{d}^{-1}$. A positive slope indicates a recharge, which is higher than the pumped yield. This occurs during long duration rainfall episodes, with an average water value lower than 120 mm. Point groups 4 and 5 are composed of these high slopes and represent about 20% of the experimental curve (Fig. 3E). Group 4 can be described by a highly significant linear correlation between the segment slope and pumped yield, which ranges from 1100 to 1600 $\mathrm{m}^3\ \mathrm{d}^{-1}$ (slope of the regression line $= -2 \times 10^{-6}Q + 0.0022$, with $r = 0.94$). Group 4 represents the effect of pumping rates significantly

Fig. 3. Separation of the curve dynamic level versus cumulative pumped volume since the beginning of exploitation: (A) measured curve; (B) separation of the measured curve into straight segments; (C) correlation between straight lines slopes and mean daily pumped yield; (D) straight segments corresponding to the slopes of the nuages 1, 2 and 3; (E) straight segments corresponding to the slopes of groups 4 and 5.

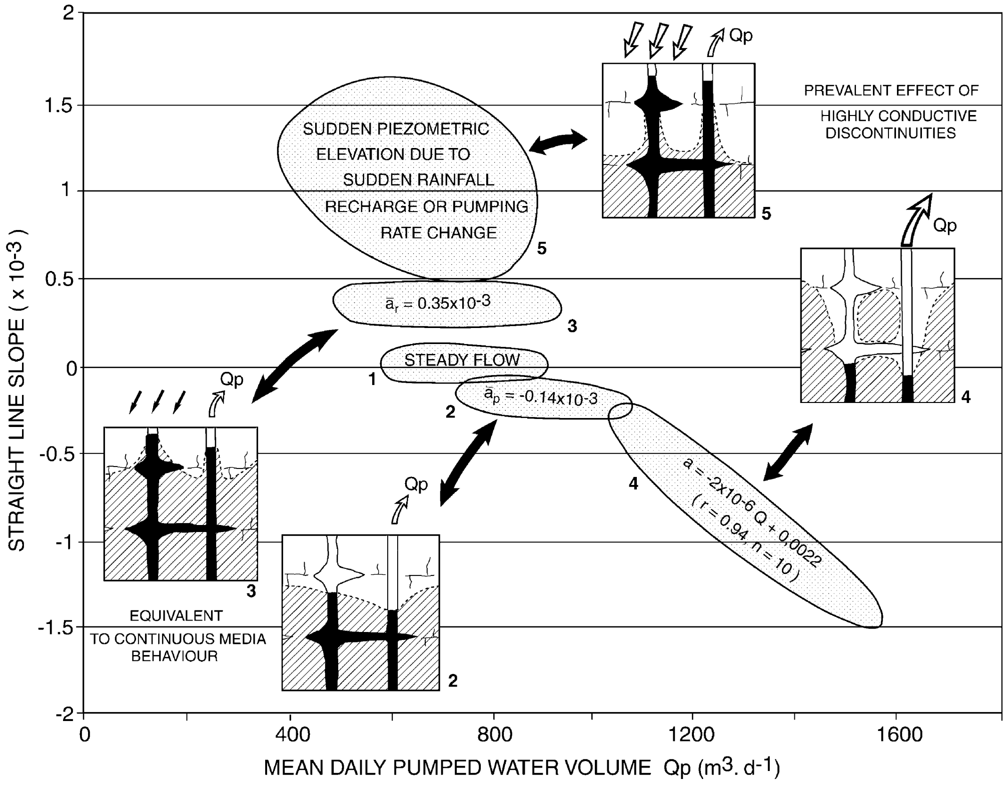


Fig. 4. Conceptual hydrogeologic model, explaining the relationship mean pumped yield versus strait lines slopes.

exceeding the discharge of the aquifer fine fissures. Group 5 is composed of the highest positive slopes. They represent rapid groundwater rises either after pumping stopped, or after heavy brief precipitation events, higher than 120 mm. The absence of correlation in this group indicates the non-linearity of the phenomenon, which may result from the heterogeneity of infiltration conditions in a karst aquifer.

4. Interpretation and resource management simulation

4.1. Interpretation

More than 80% of the plot of water level in the borehole versus cumulative yield can be described by the linear segments. Firstly, the linearity of the relationship demonstrates that the karst-fissured medium can be likened to an equivalent continuous porous medium aquifer for very long duration aquifer tests. Secondly, in the relationship

$$s = aQ + bQ^2,$$

where s is the lowering of groundwater level; a and b the constants of the curve and Q is the pumping yield, which is commonly adopted for the interpretation of aquifer tests in a continuous medium, the term bQ^2 can often be neglected.

On the diagram of slope versus average pumped volume, it is possible to explain the $s = f(Q)$ relationship by a conceptual hydrogeological model of the borehole–aquifer system (Fig. 4). The relationship $s = aQ$ corresponds to the aquifer behavior which is described by the groups of points 1–3. For pumping rates ranging from 600 to 1000 $m^3.d^{-1}$, head losses which accompany pumping fluxes are negligible ($bQ^2 = 0$). In the fractures, the water level remains connected to the one of the low permeability fine

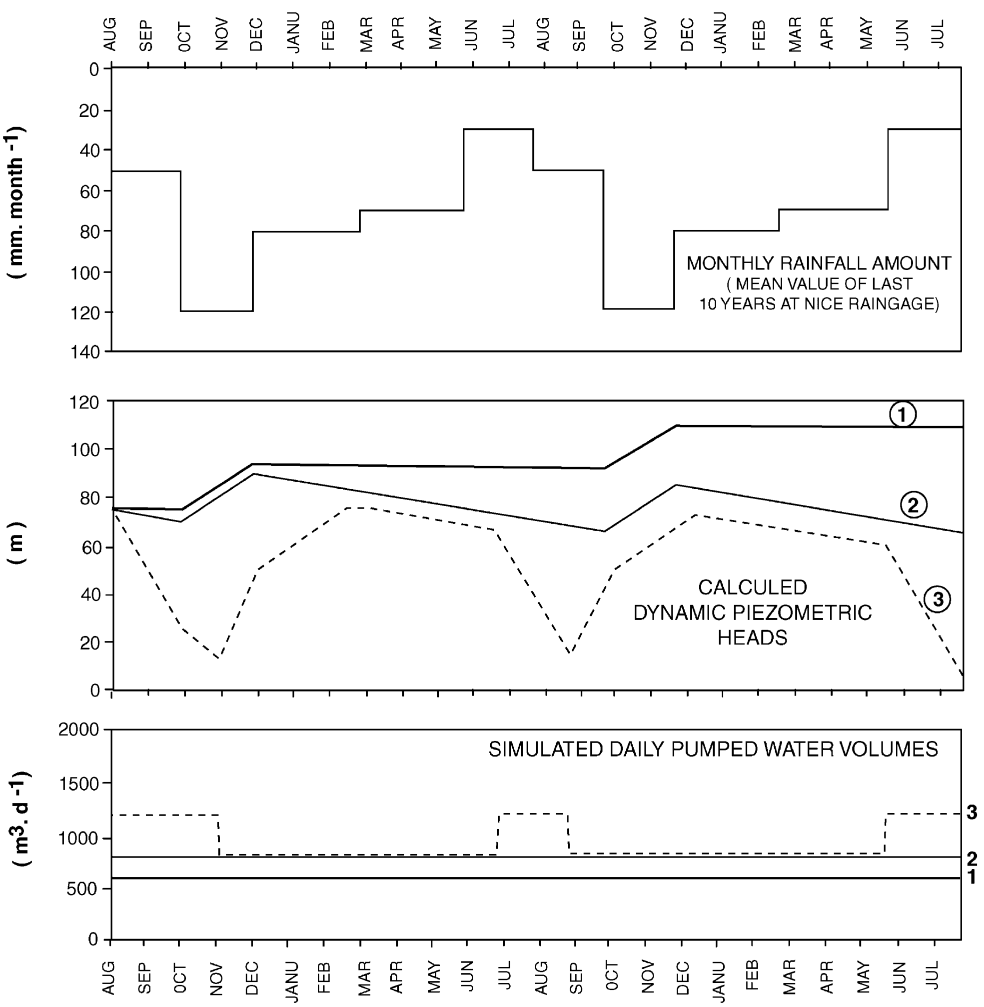


Fig. 5. Exploitation scenarios of the aquifer in borehole F1 for a 2-year duration (the curves 1, 2 and 3 correspond to three exploitation scenarios).

fissures (blocks) because of the slow drawdown (Fig. 4, groups 2 and 3). Two values of a is used to describe nearly all the recharge (a_r, group 3) and all the depletions of the aquifer (a_p, group 2). These two constants characterize the hydraulically active zones of the reservoir, the zone submitted to recharge and the exploitable zone, which indeed can be partly common. The term bQ^2 must be taken into account for the cases presented in groups 4 and 5. It represents head losses in the borehole or, in its vicinity, in drains which are directly connected to it. These head losses are significant when the drains are emptied by a major increase of the pumping rate (from 800 to >1200 m^3 d^{-1}, group 4) or refilled by a heavy rainfall (>120 mm in a short period, group 5). In both cases, the water level in the drains is disconnected from the reminder of the reservoir (Fig. 4, groups 4 and 5). The discontinuous behavior of the aquifer is then prevalent. This phenomenon is very localized in several open fractures of the reservoir (because it is only observed in piezometers P2 and P5). It has a low effect on the long-term behavior of the aquifer because it represents short duration exceptional events at the considered scale of time (several days).

4.2. Simulation of the resource management

This simulation is only valid for a long time scale (2 years), because the behavior of the borehole–aquifer system is similar to that of an equivalent continuous medium ($s = aQ$). We took into account three values of pumping, 600, 800 and 1200 $\mathrm{m}^3\,\mathrm{d}^{-1}$, which correspond to the average figures of the presently exploited yields (Fig. 5). For 1 year, the seasonal effect of recharge was evaluated by averaging the monthly rainfall at the Nice airport weather station over the past 10 years. The normal yearly climatic effect corresponds to an alternation of dry periods (from January to March and June to September), when it rains about 60 mm per month, and wet periods (from April to June and October to December), when it rains about 180 mm per month.

Three exploitation cases have been tested for a same natural recharge context during a 2-year period:

a 600 $\mathrm{m}^3\,\mathrm{d}^{-1}$ continuous pumping (Fig. 5, curve 1);
a 800 $\mathrm{m}^3\,\mathrm{d}^{-1}$ continuous pumping (Fig. 5, curve 2);
a 800 $\mathrm{m}^3\,\mathrm{d}^{-1}$ pumping until June, then increased to 1200 $\mathrm{m}^3\,\mathrm{d}^{-1}$ from July to September, and then a 800 $\mathrm{m}^3\,\mathrm{d}^{-1}$ pumping (Fig. 5, curve 3).

The 600 $\mathrm{m}^3\,\mathrm{d}^{-1}$ continuous pumping induces a low drawdown in the borehole. The effect of natural recharge is prevalent because, at the end of the period, the water level rose. The 800 $\mathrm{m}^3\,\mathrm{d}^{-1}$ continuous pumping induced a slightly greated drawdown (declining of 4–5 m). During the whole period, the pumped yield exceeded the rainfall. This induces a 10 m head reduction compared to the initial level and demonstrates an exhaustion of the reservoir (0.5 m month^{-1}). The 1200 $\mathrm{m}^3\,\mathrm{d}^{-1}$ exploitation during the summer drought induces high drawdowns which are not balanced by natural recharge. In the long run, the exhaustion of the reservoir is greater compared to the previous case (20 m lowering overall). These simulations demonstrate that the management conditions of the aquifer for a yield higher than 600 $\mathrm{m}^3\,\mathrm{d}^{-1}$ provoke a more or less significant long-term exhaustion. Particularly, pumping even higher than 1000 $\mathrm{m}^3\,\mathrm{d}^{-1}$ limited to one or two drought months may spoil the exploitable reserve for several years.

5. Conclusions

The relationship between dynamic head and pumped yield appears as linear during 80% of the five monitoring years of the Pinchinade exploitation borehole. The reservoir though it is fissured and karstified, can be considered as an equivalent continuous medium. This medium is characterized by two constants for the rate of head change in the borehole. The inverse of the drawdown slope directly yields the specific volume of the exploitable aquifer per metre of drawdawn (7143 $\mathrm{m}^3\,\mathrm{m}^{-1}$ in the case of Pinchinade). This value, as well as the transmissivity which is usually determined by aquifer tests, is an intrinsic parameter of the reservoir. It enables establishment of management scenarios, which are representative of the actual exploitation conditions. The critical Pinchinade investigation demonstrates that a simplification of the hydraulical behavior of a complex fissured medium is possible only if the aquifer tests have been performed with sufficient duration. These tests, which can be assessed over a one to three month period (monitoring necessary and sufficient to obtain a statistically representative sample of lines), greatly exceed the times usually spent for such tests.

These results demonstrate two significant factors. The first is a hydrogeologic one: the behavior of the aquifer can be different, according to the pumping rate. With a low pumping rate, the aquifer can be considered as an equivalent continuous medium. The aquifer displays its actual behavior with a dual permeability only with a high pumping rate. The second factor applies to resources management: this study demonstrates the necessity of repetitive head measurements in order to refine the optimal pumping rate, according to the recharge conditions and the management schemes.

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