Hydrogeological modeling of El Berrocal site

Modelación hidrogeológica de El Berrocal

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RESUMEN

Se sintetizan los principales resultados de la caracterización hidrogeológica del Berrocal. A escala regional, el régimen de flujo queda definido por la topografía. Ello conduce, en la zona de estudio, a un flujo vertical hacia abajo que queda localmente afectado por diques y arroyos. Se han realizado multiples ensayos de bombeo a diversas escalas. Si bien la conductividad media parece crecer con la escala del ensayo, este aumento resulta ser sólo aparente y es debido a que los ensayos de larga duración tienden a hacerse en las zonas más permeables. Los ensayos entre sondeos interpretados con modelos 3D que contienen las fracturas dominantes y que ajustan bien los datos, conducen a permeabilidades sorprendentemente parecidas a las obtenidas en ensayos de sondeo único.

ABSTRACT

Main results of El Berrocal hydrogeological characterization are summarized. Flow is controlled by topography at the regional scale. This leads to a vertically downwards flux at the site, which is only modified by preferential flow paths (veins) and local discharge points (La Tarica stream). A large number of hydraulic tests have been performed at different scales. Although representative hydraulic conductivities appear to increase with the scale of measurement, we show that such increase is caused by the fact that long-term test are performed in the most conductive zones. When these tests were interpreted by means of 3D models with embedded 2D fractures, which lead to good fits with measured drawdowns, estimated parameters turned out to be surprisingly close to those derived from single hole tests.

Palabras Clave: *hidrogeología granitos; efectos de escala; modelos 3D*
Key words: *granite hydrogeology; scale effects; 3D models*

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Introduction

The objective of this paper is to present a brief summary of hydrogeological studies at El Berrocal. More thorough discussions are presented by Guimerà *et al.*, (1996) and Carrera *et al.*, (1996). Details on the numerical interpretation of hydraulic tests are given by Vives *et al.*, (1995). Hydrogeology of the site can hardly be understood without the contribution of geophysical and structural geology data (Marín *et al.*, 1996), litho-geochemical data (Pérez del Villar *et al.*, 1996) and hydrogeochemical data (Gómez *et al.*, 1996). Summaries of these data are presented elsewhere is this volume.

In what follows, we outline hydrogeology at the regional scale (section 2), local scale (section 3) and a numerical model for the interpretation of a cross-hole test (section 4).

The regional scale

Regional scale hydrogeology was analyzed by integrating geological and geophysical mapping with water balance and recharge estimations, chemical and isotopic analyses of springs water and water head elevations. Overall, these studies allow us to conclude that regional flow is controlled by topography (much more so than in large sedimentary basins). Large scale geometry of flow paths is described in Figure 1, which explains why very large vertical gradients are observed at El Berrocal site. Figure 1 also shows that water discharges not only through springs situated at local topography minima or at the contact with the adjacent tertiary basin (where the change in surface slope leads to water table intersecting the ground surface) but also at the Alberche River.

The head evolution of borehole S-12 (Figure 2), which was used for mass balance computations, illustrates many typical features of mountaineous regions hydrogeology (see, e.g., Carrera *et al.*, 1993). Large storms tend to saturate a portion of the upper, unsaturated zone. Since this zone tends to be very transmissive, sudden rises of head dissipate rapidly until the water table falls below the high conductivity layer and decline slowly afterwards. In S-12, the transition between high (altered) and low (unaltered) conductivity zones falls around 867 m.a.s.l. This explains why heads remain relatively stable (i.e. without falling) despite the large observed gradients. A similar observation can be made about flowrates at springs.

When coupling the spatial picture (Figure 1) with the transient behaviour, it becomes apparent that the geometry of flow paths near the surface is highly variable both in space and time. During the winter, every topographical low is likely to produce a local discharge, which often becomes dry during the summer. On the other hand, the flow field at depth is much more stable, both because heads fluctuate much less than near the surface and because they do it in a more uniform way, so that head gradients change little.

The site scale

As mentioned in the introduction, data collection at the site scale was very intensive. All boreholes were cored and the cores were submitted to a large number of tests (visual mapping, mineralogical analyses, trace element, fissure filling characterization, etc). Geophysical logs of the boreholes were complemented with measurements of head and hydraulic conductivities. Oriented televiewer logs were produced at each borehole, so that absolute orientation and dip of each fracture could be obtained. Samples were taken at water bearing fractures and at producing points of the mine. Flowrates were monitored at the latter and at local springs. Samples were analyzed for major and trace elements as well as for isotopes. These data produced a consistent conceptual description of geology, hydrology, geochemistry and hydrochemistry of the site. A synthesis on such description can be derived from Figure 3, which displays head of both a horizontal and vertical cross-section.

The horizontal gradient is small towards the North, where the water divide is located and where vertical gradients are maxima, which is consistent with the regional flow scheme shown in Figure 1. In fact, the vertical gradient in S-16 (to the right of the vertical section in Figure 3) exceeds 0.2. Closer to the mine, head contours reflect the fact that the mine acts as a sink, which is clear both in the vertical cross section and in the plan view. Actually, the high transmissivity of the U-Q vein, which had been largely mined out many years ago, can also be derived from two features of Figure 3: 1, contours become parallel to the vein and, 2, head gradients to the South of the mine is much lower than to the North, hence leading one to conclude that a large portion of the flux is being taken by the vein itself. Further South, not shown in the Figure, groundwater near the surface is flowing to the Tarica stream.

A large number of hydraulic tests were performed at different scales. Most cross-hole tests were linked to water sampling motivated by hydrogeochemistry needs. Coupling sampling and testing reduced characterization time and cost, although it

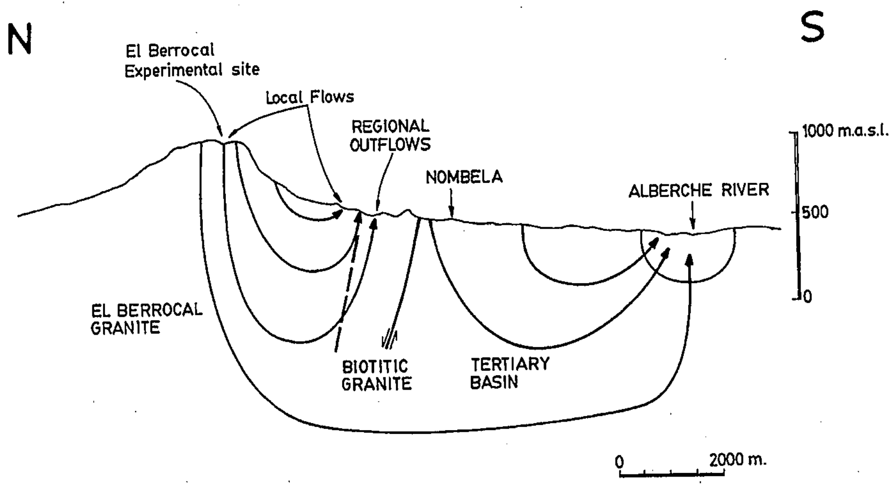

Fig. 1.- Qualitative description of the regional flow system.

Fig.1.-Descripción cualitativa del sistema de flujo regional.

required increased coordination among the teams involved in the project. Hydraulic conductivity of the site is extremely variable. Most measurements were taken over 10 m intervals (down to 3 m long intervals were tested for isolated fractures) and rangedbetween 10 m/s (with some intervals falling below this lower detection limit) and 10 m/s (at the U-Q vein).

A question that often arises when analyzing the spatial variability of hydraulic conductivity is to find out whether a large scale equivalent value can be derived from small scale tests. This is critical because characterization of permeable media is based on small scale tests while the behavior of the medium as a whole is controlled by large scale values. Several authors, notably Clauser (1992), have reported that hydraulic conductivity increases with the scale of measurement beyond what should be expected. In order to study possible scale effects at El Berrocal, Guimerà *et al.*, (1995) summarized all estimates of K as a function of size of the rock volume contributing to the estimation. Results are shown in Figure 4.

A cursory examination of Figure 4 might suggest that scale effects are indeed present at El Berrocal. However, Guimerà *et al.*, (1995) argue that the scale dependence of El Berrocal

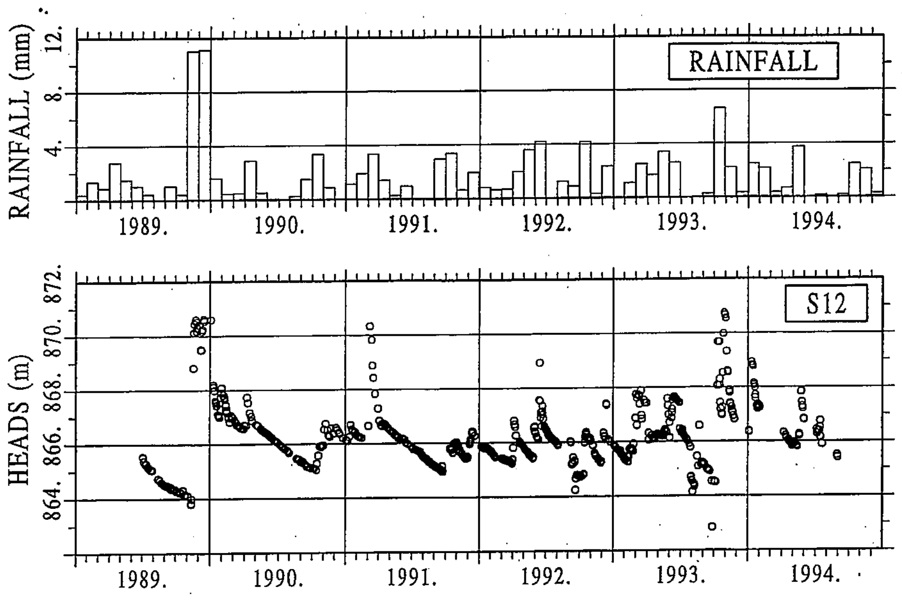

Fig. 2.- Evolution of heads at borehole S12 along with monthly rainfall. Notice that heads decline slowly below 867 m.a.s.l.

Fig. 2.- Hidrograma del sondeo S12 y lluvias mensuales. Nótese que la velocidad de descenso se reduce cuando el nivel está por debajo de 867 m.s.n.m.

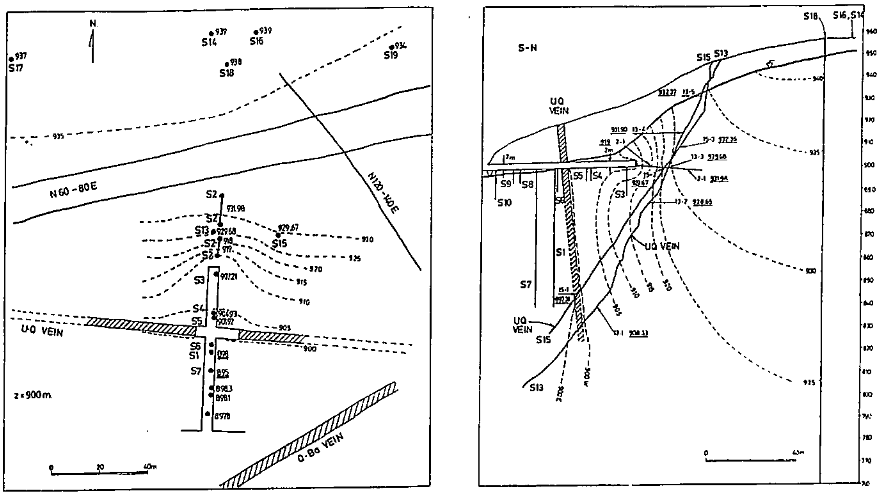

Fig. 3.- Plan view of head contours at an elevation of 900 m (left) and at a vertical cross section along the mine (right). Notice the effect of the mine and uranium-Quartz vein in both graphs.

Fig. 3.- Isopiezas en planta a la cota de 900 m (izda) y en sección vertical por la mina (dcha). En ambos gráficos se puede observar el efecto sumidero de mina y dique.

hydraulic conductivity may be an artifact, resulting from a bias in the sampling procedure. Intermediate scales estimates of hydraulic conductivity are based on long tests and/or cross-hole tests. These were normally performed during water sampling and their location was chosen so as to ensure that a large volume of water could be extracted. In short, pumping sections were selected on the basis of a high local transmissivity. Hence, it is not surprising that the corresponding values

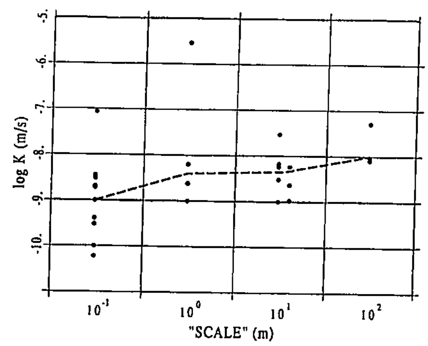

Fig. 4.- Summary of K values obtained at different sacles. Each do not at the 0.1 m scale represents the median of the K values obatined with the same packer spacing at each well. Notice that there is a one order of magnitude increase in median K when increasing the scale from 0.1 to 100 m (Guimerà et al., 1995).

Fig. 4.- Síntesis de valores de K obtenidos a varias escalas. Los puntos de escala de 0.1 m representan la mediana de los valores obtenidos en cada sondeo con intervalos constantes entre obturadores. Notese el aumento de un orden de magnitud al aumentar la escala de 0.1 a 100 m.

of large scale conductivity are larger than the average. Finally, the 100 m scale estimates are based on vertical plane flux estimations. Since most high transmissivity fractures are subvertical, one would also expect the corresponding estimates of hydraulic conductivity to be significantly larger than those derived from single hole tests. In summary, it cannot be stated that K increases with scale at El Berrocal. In fact, when large scale (cross-hole) tests are interpreted with non-homogeneous models, results are surprisingly consistent. This issue will be discussed in the next section.

Numerical modeling of cross-hole tests

One of the conclusions from the previous section is that homogeneous models may not be adequate for interpreting large scale tests. Therefore, we opted for using a numerical model capable of accounting for heterogeneities. Specifically, our conceptual model is based on assuming that most water flows through a few dominant fractures, while the rest can be lumped in a porous medium. We have tested this concept with good results in other sites (Carrera *et al.*, 1989; Sánchez-Vila *et al.*, 1993). However, the volume and quality of data available at El Berrocal Allowed us a more thorough test of the model. This type of conceptual model was applied to all cross-hole tests. However, because of space constraints, we will only discuss the interpretation of the test performed by extrating a 0.1 l/min flow rate from S-2 while observing the response at several intervals of S-13 and S-15.

The low permeability nature of the medium imposes a series of difficulties during the interpretation of the test. For one thing, pumping rates have to be small. Hence, the response is weak and the test must last for long. Because of the long duration, natural head variations may be significant and they have to be filtered out from data prior to test interpretation. Moreover, factors that can be neglected in "normal" media may become dominant in this type of low permeability media. Such is the case with wellbore storage or wellbore shortcircuiting, both of which make it important to explicitly simulate the well. In summary, extreme care must be taken to account for all the factors that may affect the tests. Ways of handling them are discussed by Carrera *et al.*, (1996).

Geometrical characteristics of the model used for interpreting the S12-S13-S15 test are summarized in Figure 5. Note that a 3-D domain with two embedded fractures (F1 and F2) has been used. These fractures had been identified as the most important ones while testing the boreholes. Both of them appear to either intersect or be very close to S2. A high T layer has been superimposed on the upper boundary of the model to represent the high T, phreatic layer.

Several tests were performed with this geometry. Calibration fits displayed in Figure 5 are the ones corresponding to the longest lasting and best controlled one.

While drawdown fits are quite good, the most interesting results come in terms of estimated parameters. Overall hydraulic conductivity for the porous domain turned out to be 2.7 10^{-10} m/s, while the median of the S13 borehole (excluding fractures) was 4.0 10^{-10} m/s and that of S-15 was 2.0 10^{-10} m/s. Transmissivity of fracture F1 was equal to 5.5 10^{-8} m^2/s, while the value derived from the single hole test at its intersection with S-13 was 4.0 $10^{-8}$$m^2$/s. Finally, calibrated transmissivity of fracture F2 ranged between .5 and 4.0 10^{-8} m^2/s depending on calibration assumptions, while the measured value at the intersection with S-15 was10^{-8} m^2/s. In short, consistency between calibrated parameters and those derived from single hole tests is excellent. The agreement is even better in some of the other tests. These are indeed good news because they point out that flow through fractured media is predictable.

Conclusions

Several types of conclusions can be derived from the work performed at El Berrocal, only a portion of which has been summarized here. Site specific hydrogeology can be summarized by stating that deep recharge ranges between 10 and 50 mm/year.

Hydraulic conductivity of the rock mass falls around 10^{-8} - 10^{-10} m/s, while transmissivity of preferential flow paths falls around 10^{-6} - 10^{-7} m/s. Local flow is controlled by local factors (preferential flow paths, the mine, the Tarica stream) and regional topography, which exerts a very large vertical downward gradient between 0.1 and 0.4.

A number of conclusions about the hydrogeology of low permeability fractured media can also be derived:

^ Apparent scale effects on hydraulic conductivity turned out to be an artifact resulting from the fact that the most permeable intervals were chosen for cross-hole tests.

In fact, when cross-hole tests were analyzed using non-homogeneous models, it could be seen that calibrated parameters (porous domain k and fractures T) were surprisingly close to those derived from single hole tests. Since the latter are the only ones that one can realistically expect to measure at a real site, this result suggests that one can indeed obtain a good model on the basis of single hole data.

^ Modeling capabilities specifically developed for El Berrocal project include the possibility of calibrating models with some significant fractures embedded in a 3-D porous domain. This type of models has been able to properly simulate a number of hydraulic tests. In fact, it also has been used to simulate tracer tests, which are described elsewhere in this volume.

^ A comprehensive conceptual model of the site has been produced by coupling geological, hydrochemical and hydraulic approaches. While this type of coupling is advisable in any media, its need becomes much more important in low permeability fractured media, where heterogeneity is very large and where hydraulic data may not be very informative.

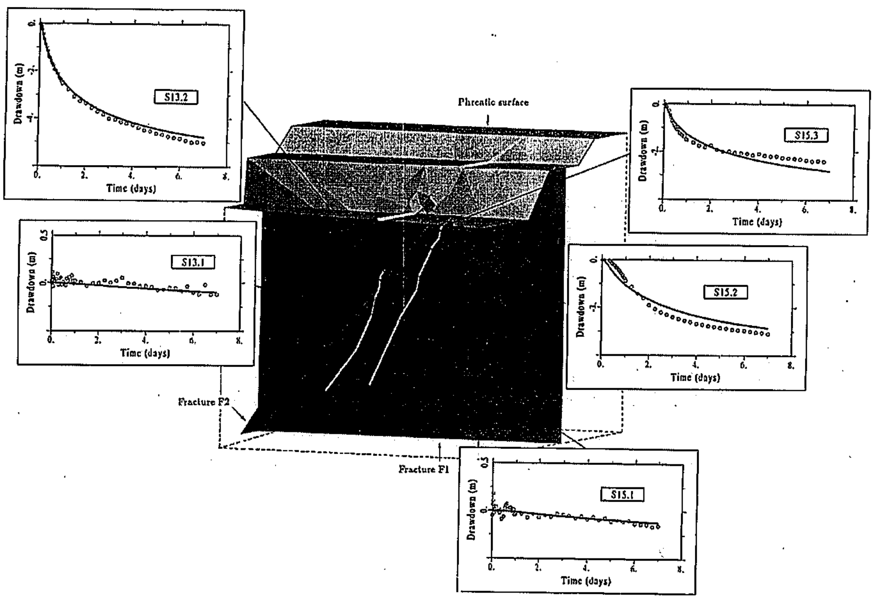

Fig. 5.- Grid for 3D model interpretation of the S2-S13-S15 pump test. Also shown is the fit between measured and computed drawdowns after calibration. Notice that boreholes and fracture planes (including the altered layer at the phreatic surface) are modeled explicitly.

Fig. 5.- Malla 3D para la interpretación del ensayo S2-S13-S15. También se muestran los ajustes obtenidos en los descensos. Notese que tanto los sondeos como las fracturas y la capa alterada superficial se modelan explícitamente, superponiéndolos a la malla 3D.

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