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Approche à différentes échelles pour la caractérisation hydrodynamique d'un aquifère de socle : le cas d'étude des métaarénites paléozoïques de Sardaigne (Italie)

Multi-scale approach in hydraulic characterization of hard rock aquifers: a case of study from Paleozoic metarenites of Sardinia (Italy)

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I. INTRODUCTION

Hard-rock aquifers, such as those constituted by plutonic and metamorphic rocks, are recognized to be highly heterogeneous, particularly in relation to the different degrees of fracturing. This implies that the bedrock transmissivity can vary over many orders of magnitude. Therefore, well yields are highly variable, and a high incidence of well failure occurs. Thus, defining a sustainable pumping rate is more difficult here than in other cases because of the extremely complex aquifer behavior. In this case, more so than in other cases, considerations of the discontinuous flow system, anisotropy and heterogeneity are required to develop a reasonable model of the aquifer.
In Italy, where hard rocks outcrop over large areas in the Alps, Calabria and Sardinia, the hydrogeological properties of plutonic and metamorphic rocks are not well known. The groundwater yields of these aquifers (generally less than 5×10^{-3} m^3/s per km^2) are lower than those in the more common carbonate and alluvial aquifers (up to 3×10^{-2} m^3/s per km^2), which are widely used for the water supply. The interest in hard-rock aquifers is thus generally scarce; nevertheless, the large extent of these rocks and the scarcity of water resources in Sardinia and Calabria justify a thorough analysis. This is the context of our study, which concerns a dam site in metamorphic rock in southern Sardinia.

II. STUDY AREA

The area under examination was 25 km west of the town of Cagliari, in the Sardinia region (Fig. 1), where the Paleozoic basement related to the Hercynian orogenic evolution outcrops.
The Paleozoic basement consists of an originally sedimentary succession (Lower Cambrian to Early Carboniferous) that was deformed during the Carboniferous period under the low metamorphic to anchizonal setting. The Arburese Unit outcropping at the dam site consists of the Arenarie di San Vito Formation (Middle Cambrian to Lower Ordovician), which is several hundred meters thick and is composed of decimetric to metric alternations between micaceous metasandstones, quartzites and metasiltstones.

The structural framework is mainly linked to the Hercynian Orogeny and Pliocene tectonic events (Barca et al., 1981; Carmignani et al., 2001).
The study site corresponded to the building zone of the Medau Zirimilis Dam (Fig. 1), a 50-m-high rockfill dam that was completed with an upstream impervious face and with a grout curtain 10-50 m deep.
During the construction of the dam and the initial reservoir filling, several hydrogeological investigations were conducted. One of these was the measurement of the seepage through the rock foundation and laterally to the dam, that could be observed in the drainage systems located at the base of the dam embankment and downstream of the grout curtain. These and other investigations highlighted the fact that the groundwater circulation involved the most fissured layers closest to the surface, including, on average, the first 50 m of the Paleozoic rocks, up to a depth of 100 m in the faulted zones. The most evident faulted zone has been found in the valley bottom at the site of the dam (Celico et al., 1993).

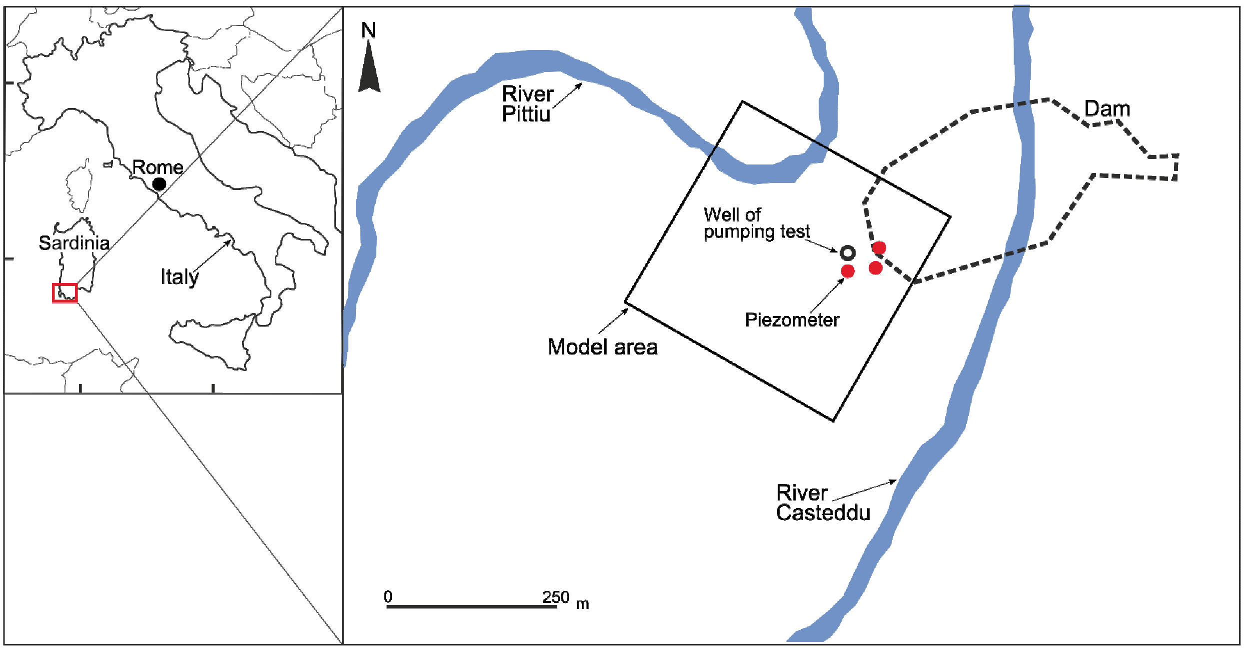

Figure 1 – Location of the study area.

III. INVESTIGATION AND RESULTS

The results of the previous surveys (Celico et al., 1993) have been revised, integrated and appropriately processed to obtain the hydraulic characterization of the Palaeozoic rocks. The field investigations at the dam site included a surface fracture survey, injection tests and pumping tests.
The surface fracture survey concerned the Arenarie di San Vito Formation. Two discontinuity types were identified in the examined outcrops (Fig. 2). The first type consisted of regular bedding planes that were continuous at the scale of the outcrops and delimited the various metasandstone and metasiltstone beds. The second type of discontinuity consisted of sub-vertical straight joints of varying orientations that cut the bedding planes.
A simplified model of the fracture network has been considered for a first estimate of the hydraulic properties of the rock mass. According to the cubic law (Snow, 1969), hydraulic conductivity of 5×10^{-6} m/s for the bedding planes, and from 1×10^{-5} to 3×10^{-5} m/s for the two sub-vertical fracture sets were determined. Values and orientation of the major, intermediate and minor components of the hydraulic conductivity of rock mass resulted, respectively: 4×10^{-5} m/s and 359°/74°; 3×10^{-5} m/s and 109°/6°; 2×10^{-5} m/s and 201°/15°.

Figure 2 – Discontinuity network of the Arenarie di San Vito Formation.

A total of 76 injection tests (Lugeon tests) were performed in 8 boreholes penetrating the Arenarie di San Vito Formation to a maximum depth of 60 m; one of the boreholes was drilled with a dip angle of 60°. The hydraulic conductivity in each test interval was calculated by applying the Moye equation (1967). The calculated values fell within three orders of magnitude (10^{-8} – 10^{-6} m/s), with a geometric mean of 2.81×10^{-7} m/s. At depths greater than 25 m, there was a significant decrease in the hydraulic conductivity, with the exception of the inclined borehole. Above a depth of 25 m, the boreholes that were located in the valley bottom, corresponding to a faulted zone, exhibited a higher hydraulic conductivity.
During the initial reservoir filling, pumping tests were performed at five wells, with depths between 73 and 100 m. The pumping tests lasted between 7.5 and 45 h at a constant rate between 2.1×10^{-3} and 3.5×10^{-3} m^3/s, with the observation of a drawdown in at least one piezometer nearby the tested well.
The pumping test data diagnosis included a comparison of the drawdown plots of each piezometer with theoretical models to determine the aquifer parameters. For wells with more than one piezometer, there was a simultaneous response in the pumping, and generally, a similar shape for the drawdown curve for the different observation wells was reported.
The overall transmissivity and storage coefficients varied from 2.3×10^{-4} to 3.6×10^{-3} m^2/s and from 3.1×10^{-5} to 2.6×10^{-2}, respectively. The transmissivities were converted into hydraulic conductivities based on the saturated aquifer thickness intercepted by the tested well. The values fell in the range of 4.6×10^{-6} - 4.1×10^{-5} m/s, with a geometric mean of 1.68×10^{-5} m/s.

IV. CONCEPTUAL MODEL

The surface fracture survey provides a model of rock mass that is characterized by a well-developed discontinuity network (three discontinuity sets), a high frequency of discontinuities (spacing of less than 0.5 m) and comparable values of the average apparent aperture of the different sets (approximately 0.1 mm). The discontinuity network gives rise to a slight anisotropy in the medium, with the major principal component of the hydraulic conductivity directed vertically downward.
The injection tests clearly showed the extreme heterogeneity of the rock mass, as highlighted by the wide range of values determined for the hydraulic conductivity (10^{-8}–10^{-6} m/s). The highest values of hydraulic conductivity were found for the inclined borehole, which was close to the fault zone and thus intercepted a great number of vertical fractures. With the exception of the inclined borehole close to fault zone, the hydraulic conductivity was observed to diminish below a depth of 25 m.
The hydraulic conductivity derived from the pumping tests covered a lower range of values (10^{-6}–10^{-5} m/s) than did those calculated using the injection tests. No particular trend was evident from the comparison of

the values of hydraulic conductivity obtained for piezometers located in different directions from the pumped well. The variation in the parameter is therefore attributable to the heterogeneity of the aquifer rather than to its horizontal anisotropy.
The comparison between the hydraulic conductivity determined by the injection tests and the pumping tests revealed values that were substantially lower in the first case. This can be attributed to the limited volume of rock mass affected by the injection tests compared to that affected by the pumping tests. In both cases, the hydraulic heterogeneity of the rock mass was evident. The injection tests and the pumping tests also converged and indicated higher hydraulic conductivities near the fault that runs in the valley of the dam site.
The conceptual model was completed by a potentiometric surface reconstruction over the entire dam site using the head data measured in 70 wells and boreholes during the initial reservoir filling when the artificial lake level was at 121 m asl. It appears that the head contour lines generally replicate the topography, higlighting relationships between groundwater and the artifical lake and streams.

V. NUMERICAL MODEL

A simplified numerical model was constructed in the western sector of the dam site (Fig. 1), where a well tested during pumping tests falls and nearby the outcrops of the surface fracture survey. The model was implemented with the code MODFLOW-2000 (Groundwater Vistas 6 graphical user interface). Initial heads, geometry of the model, aquifer charateristics and boundary conditions were obtained from the investigations and from the conceptual model.
The model underwent an initial calibration through the trial-and-error technique. This step preceded the application of the parameter estimation code PEST 13.0 (Doherty, 2010), which was applied in two different modes: zone calibration and pilot point calibration.
A steady-state calibration was used as the first time period of the transient simulation. A second time period, divided into 20 steps, was introduced with pumping from the well at a constant rate for 19 hours. Transient data were calibrated for the pumping well and two piezometers.
Calibrated model gives ranges of transmissivity from 5.0×10^{-6} to 2.5×10^{-3} m^2/s.

VI. CONCLUSION

Investigations concerning fractured metamorphic rocks in a representative area of Sardinia can be used to hydrogeologically characterize these low-permeability rocks and to examine which approach can be used to represent the fractured aquifer.
The results of the surface fracture survey implied the possibility of considering the fractured medium as an equivalent porous medium at the outcrop scale, because the discontinuity network gives rise to a reduced representative elementary volume (less than 1 m^3) for the rock mass. The injection tests showed an extreme heterogeneity and a lower hydraulic conductivity of the rock mass (10^{-8}–10^{-6} m/s) in comparison with the results of the pumping tests (10^{-6}–10^{-5} m/s) (Fig. 3). This scale effect of the parameter is expected in heterogeneous media (e.g., Clauser, 1992; Schulze-Makuch et al., 1999; Renard and de Marsily, 1997; Neuman and Di Federico, 2003) because the volume investigated by the injection tests was significantly smaller than that of the pumping tests. Regarding the latter type of tests, if we consider the simultaneous response to pumping and the similar shape of the drawdown curves for the different piezometers when the pumping was performed from the same well, the porous medium approximation appears appropriate.
The numerical model considered one representative pumping test and provided additional information on the hydrogeological characterization of the hard rocks.
The results of the field investigations together with the model output would encourage the equivalent porous approach. The estimate of transmissivity resulting from the model highlighted a range of values higher than those resulting from the pumping tests. However, the transmissivity values determined in the pumping tests (from 10^{-4} to 10^{-3} m^2/s) fell in the range of the calibrated values of the model (from 10^{-6} to 10^{-3} m^2/s), with a common upper limit of the parameter (Fig. 3). This still seems to be consistent with what is

reported in the literature, i.e., that the increase in average permeability apparently does not continue from the pumping test to a regional scale (Clauser, 1992; Schulze-Makuch et al., 1999). On the other hand, four orders of magnitude of transmissivity obtained from the model compared with two orders of magnitude from the pumping tests, highlight a higher hydraulic heterogeneity of the aquifer, this time in agreement with the results of the injection tests.

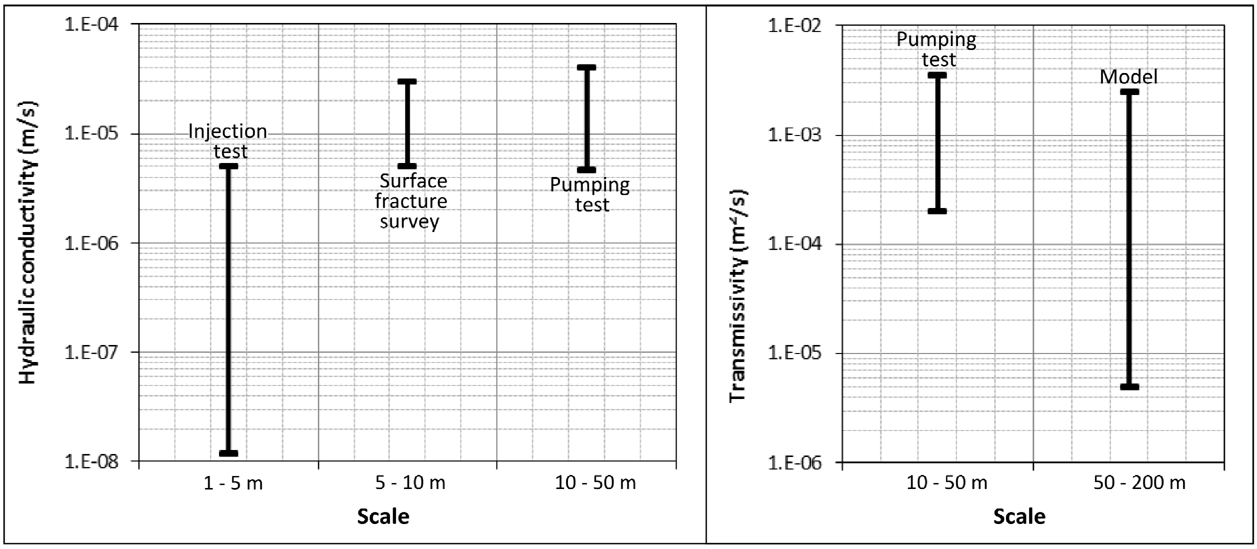

Figure 3 – Hydraulic parameters and scale of measurement of the different methods used.

Refererences:

Barca S., Cocozza T., Del Rio M., Pittau Demelia P. (1981). - Discovery of lower Ordovician Acritarchs in the "Postgotlandiano" sequence of southwestern Sardinia (Italy): age and tectonic implications. *Bollettino della Società Geologica Italiana, 100, 377-392.*

Carmignani L., Conti P., Barca S., Cerbai N., Eltrudis A., Funedda A., Oggiano G., Patta E.D. (2001). - Note Illustrative della Carta Geologica d'Italia 1:50.000 "Foglio 549 – Muravera". Servizio Geologico d'Italia, Roma.

Celico P., Piscopo V., Berretta G. (1993). - Influenza di un invaso sulla circolazione idrica sotterranea in rocce scistose. *Geologia Applicata e Idrogeologia, 28, 253-261*.

Clauser C. (1992). - Permeability of crystalline rocks. *EOS, 73 (21), 233-240.*

Doherty J. (2010). - PEST, Model-independent parameter estimation – User manual (5th ed). *Watermark Numerical Computing, Brisbane.*

Moye D.G. (1967). - Diamond drilling for foundation exploration. *Civil Eng. Transact. Inst. Eng., 9, 95-100.*

Neuman S.P., Di Federico V. (2003). - Multifaceted nature of hydrogeologic scaling and its interpretation. *Reviews of Geophysics, 41 (3), DOI: 10.1029/2003RG000130*

Renard P., de Marsily G. (1997). - Calculating equivalent permeability: a review. *Advances in Water Research, 20, 253-278.*

Schulze-Makuch D., Carlson D.A., Cherkauer D.S., Malik P. (1999). - Scale dependency of hydraulic conductivity in heterogeneous media. *Ground Water, 37, 904–919.*

Snow D.T. (1969). - Anisotropic permeability of fractured media. *Water Resource Research, 5, 1273-1289.*