

Temperature in the Geothermal Euganean Basin: a Simulated Annealing Approach

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Abstract: In the geothermal Euganean area (Veneto region, NE Italy) water temperatures range from 60°C to 86°C. The aquifer considered is rocky, principally extended in fractured Mesozoic limestone. For exploitation purposes, it is important to identify zones with a high probability that the temperature is higher than 80°C. First, variographic analysis was conducted from 186 data temperatures of thermal groundwaters. Then the indicator variogram at the cutoff of 80°C was analyzed. Finally, the locations of areas with a high probability of the temperature being above 80°C were identified by geostatistical simulations of spatial distribution of temperature. In order to perform simulations we use a simulated annealing procedure.

INTRODUCTION

The hydrothermal Euganean area extends on a plain band of about 20 km² immediately east of the Euganean Hills (Fig.1), comprising the territories of Abano Terme, Montegrotto Terme, Battaglia Terme and Galzignano Terme. In this area about 100 mining claims and more than 400 wells have been drilled. At present about 250 wells are active and the total average flow rate of thermal fluids in Abano and Montegrotto is about 0.1-0.2 m³/s. The Euganean aquifer is rocky and confined.

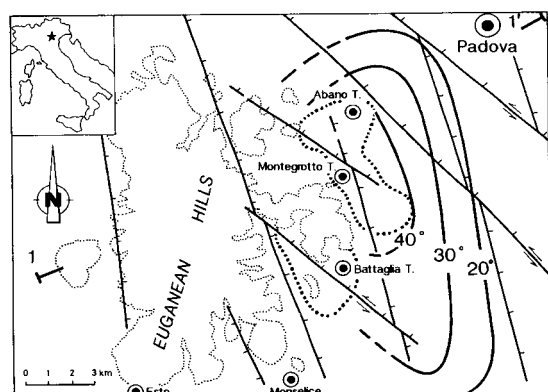


Figure 1. Structural situation of geothermal area (from Antonelli *et al.* 1995)

Most of these exploitation wells extend for several hundred meters into bedrock, however, well casing is only placed in the quaternary cover. The well depths range from about 300 m to more than 1000 m. Wells 1000 m in depth have recently been drilled in the Abano zone.

The temperature of thermal waters ranges from 60° to 86°C, and their T.D.S. is approximately 6 g/L with a primary presence of Cl and Na (70%) and secondary of SO₄, Ca, Mg, HCO₃, SiO₂.

A conceptual model of the Euganean geothermal basin was first presented by Piccoli *et al.* (1973) and it has recently been confirmed by Dal Piaz *et al.* (1994). This geothermal system has its recharge zone located in the pre-Alpine area (Piccole Dolomiti), where meteoric waters infiltrate at about 1500 m a.s.l. reaching a depth of more than 3000 m, where they are thermalized by a normal geothermal gradient. From this recharge zone the waters descend south-eastwards for roughly 80-100 km until reaching the Abano and Montegrotto areas. Recent studies now in progress regarding the residence time of the Euganean fluids and water samples of the Euganean geothermal field for ¹⁴C AMS and tritium measurements, indicate a residence time of much more than 60 years (Sartori *et al.* 1997).

In the Euganean geothermal area the fluids naturally rise by favorable tectonic conditions (Fig.1). Particularly, in the Abano and Montegrotto fields, the fluids rise from localized deep fracture zones. Moreover, when a relatively shallow high fractured carbonatic reservoir (of about 300-500 m) is achieved a horizontal hot water movement is allowed. The thermal fluids are

partially stored inside this known fractured reservoir and partially rise again into the alluvial cover until some 10 m from the surface, eventually mixing with the cold water present in the quaternary cover. In fig.2 a geological cross-section of the geothermal Euganean area is reconstructed by geological, structural, lithostratigraphic knowledge, and by geophysical investigations in the subsoil between the Euganean Hills and the city of Padova. The structural situation is connected with the activity of the extensional tectonics controlled by different fault systems of regional importance, the "Schio-Vicenza" being the most significant one.

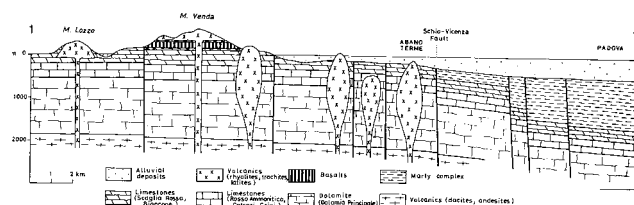


Figure 2. Cross-section of geothermal area (from Antonelli *et al.* 1995)

The analysis of the piezometric data indicates two periods (spring and autumn) of intense exploitation and two (winter and summer) of low exploitation. At present the level is, on average, about 7-10 m in depth. The comparison between the water level in the deeper and more recently drilled wells and in the other wells (300-500 m in depth) shows a very different piezometric level, but the piezometric variation of artesian wells is in agreement with the seasonal artificial variation (due to exploitation), showing a hydraulic connection between different aquifer zones. Thus all the wells are thought to produce water from different levels of the same thermal aquifer. The water level differences are linked to the high exploitation of the shallower carbonatic reservoir, essentially located in the "Biancone" fm, and to its modest transmissivity (generally ranging from 13 m²/day to 500 m²/day) (Fabbri 1997). A similar hydraulic connection was identified in the sandy aquifer at about 60 m in depth in the quaternary cover (Antonelli *et al.* 1995). In fact, its piezometric level has the same regime as the rocky aquifer, but it is only a few meters below the surface. Thus, it is possible to affirm that all the different productive levels in the geothermal aquifer from depths of 60 to 1000 m are locally interconnected and the piezometric difference is related only to the unequal exploitation of different water bearings of the same aquifer.

DATA AND VARIOGRAPHIC ANALYSIS

The 186 data of temperatures considered in this paper concern only the shallower carbonatic reservoir ranging from 300 to 500 m in depth.

In performing the geostatistical analysis the GSLIB Library (Deutsch and Journel 1998) and Variwin codes (Pannatier 1996) are used. First we perform an initial exploratory spatial data analysis, evaluating the summary statistics and the principal

spatial characteristics. The clustering of samples suggests using declustering techniques in order to have a more representative set of summary statistics. Then the study continues with the analysis of the continuity structure. Variogram cloud analysis (Ploner 1999) does not evidence the presence of outliers and allows for a decision as to which lag distance should be used to study the directional variograms. The study of directional and surface variograms shows that the continuity structure is anisotropic and can be summarized as follows. We see a middle scale anisotropic structure (anisotropy ratio of 0.6) with principal direction along 290° and a large scale anisotropic structure (ratio 0.2) with principal direction along 340° . Identification of a large scale anisotropy is very interesting because it is related to an important regional geological structure represented by the “Schio-Vicenza” fault system (Fig.1). This fault system has a direction of roughly 340° . Then indicative variograms of three statistical characteristic thresholds of univariate temperature distribution are studied (second, fifth and eighth decile). Their comparison indicates that higher temperature values are less connected in space than lower ones. This suggests taking in to account the indicative variogram of the economically important threshold of 80°C . The next step is the inference process. This is required in the case of the simulated annealing procedure because we need a theoretical variogram which exhaustively describes the data's continuity structure. This inference process is conducted for the experimental variogram but also for the experimental indicative variogram of the threshold of 80°C . The experimental variogram of temperature is fitted with a nested model composed of a nugget effect and two anisotropic spherical models. The indicator variogram of the 80°C threshold is fitted by a nugget effect and an anisotropic exponential variogram.

After the variogram analysis and the inference process, the geostatistical simulation of temperature in the geothermal Euganean area is performed.

RESULTS

The objective of conditional geostatistical simulation is to produce a set of equiprobable realizations honoring data values and some desired properties. From the analysis of these realizations we can compute spatial and local uncertainty about the phenomenon being studied. Due to the inconsistency of the multigaussian hypothesis we decide to use a simulated annealing method. This technique is not really a simulation procedure referring to a random function model but rather an optimization method. Here an initial random stochastic image of spatial distribution of temperature is perturbed until it reaches certain desired properties. In this case the desired or target properties are the inferred histogram, variogram and indicator variogram. **Sasim** code is used in order to perform simulated annealing simulations. 500 simulations of spatial distribution of temperature are made. In general, both the histogram and variograms are well reproduced.

We derive some useful maps by postprocessing the 500 simulations: one map with the probability that the temperature in the geothermal Euganean area exceeds 80°C thresholds; another map showing the “E-type” estimates of temperature and third map showing the spatial distribution of the interquartile range. By analysis of fig.3, zones with very probable high temperatures (more than 80°C) and low interquartile range may be identified.

CONCLUSIONS

In this paper the use of the geostatistical simulation to determine the probability of the temperature being more than 80°C in the geothermal Euganean area is shown. The results of 500 simulated annealing simulations of temperatures in the geothermal Euganean field are postprocessed and discussed. Here the importance of detailed variographic studies focused upon the structural variability analysis and the objective work (e.g. temperature thresholds) is pointed out, the study being approached from a hydrogeological point of view.

Finally the choice of the simulated annealing procedure represents a good “exploitation” of the variogram and statistical analysis.

The maps of the probability of the temperature being more than 80°C and the maps of interquartile range reveal some practical hydrogeological information such as (fig.3):

- the identification of an interesting unexploited zone of high temperature in the Abano field with a high probability and a low interquartile range near the “Menegolli” mining claim.
- the identification of a little exploited zone in the Montegrotto field with a high probability that the temperature is more than 80°C and a low interquartile range.
- the localization of areas between the Abano and the Montegrotto field (“Massaggio”, “Antoniana” and “Cecchinato” mining claims) with a low probability that the temperature is more than 80°C and a low interquartile range.

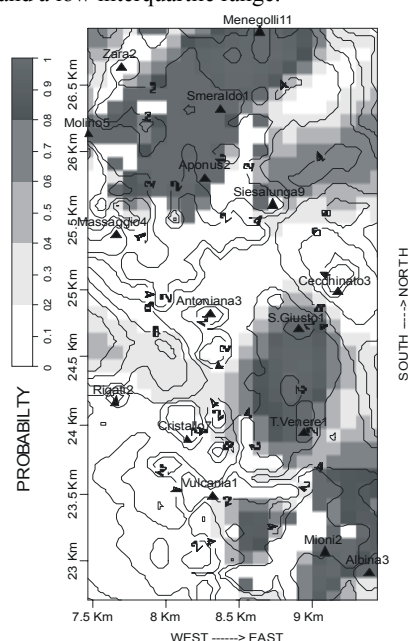


Figure 3. Probability map with superimposed interquartile range (contours)

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