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Mapping of the shallow geothermal resource and potential direct uses for the northern province of Rome (Central Italy). The Fuzzy Logic a useful analysis tool.

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Abstract:

The continuous increase in oil price and the need to reduce the greenhouse gas emissions are moving the attention to the use of the renewable such as geothermal energy. In Italy, despite the considerable geothermal know how and geothermal potential of the territory, many resources are yet untapped, especially for the direct uses. In this framework, the aim of the study is twofold: 1) mapping the shallow geothermal resource (<1000 meters of depth) in the northern province of Rome; 2) to evaluate the potential direct uses of the identified geothermal resource. The *fuzzy logic* joined to a dedicated geographical information system has been a precious tool for the intended purposes. The obtained results show that the greatest resource availability is located along the Tyrrhenian coast of the northern province of Rome, where the shallow hot fluids could be used in the agriculture, greenhouses and space heating. Moreover, Spas and teleheating could be developed in Sasso and Bagnarello, and in residential areas such as Civitavecchia, S.Marinella and Ladispoli, respectively. These results can represent a first step to renew the interest on shallow geothermics, offering a first support in the decision-making processes.

1.INTRODUCTION

Geothermal Energy is a renewable, clean and sustainable source that can be used indirectly for power generation and directly for numerous applications such as: space, district and greenhouse heating, aquaculture, agriculture and industrial processes.

The world-wide interest about the renewable energies such as geothermal energy is growing due to the urgent need to develop a strategic energy plan (EU, 2007), fundamental to solve the problem of CO_2 emission increasing.

A study published in 2006 by the European Commission (EU, 2006) shows that if existing trends continue, by 2050, CO_2 emissions will be unsustainably high: 900 to 1000 parts per million by volume.

World geothermal energy installed capacity at the end of 2009 was 10.7 GW_e for electricity generation and 50.6 GW_{th} for direct use [3 IEA 2010]. USA is the main producer in the world for geothermal electricity whereas Italy is 5th , and only at 7th place, for geothermal direct uses in Europe (fig.2) (OECD/IEA, 2010).

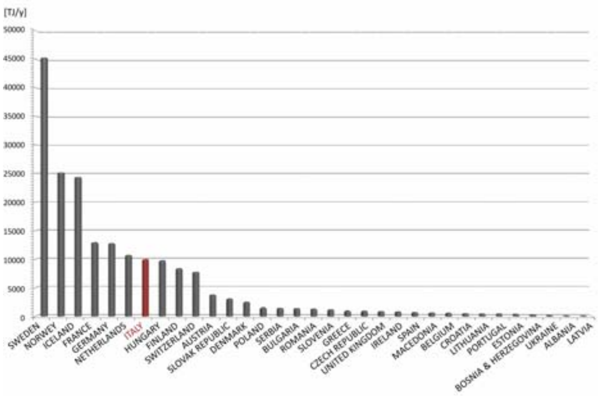

Figure 2: European ranking of the geothermal direct uses [TJ/y] on 2010 (data from Lund, 2011).

In Italy, there's a strong necessity to renew the interest for the renewable energies specially for the geothermal energy, because the Italian territory has an huge potentiality, until now not much exploitated.

For a correct choice about the direct possible use of geothermal fluids, an evaluation of the characteristics of the resource (temperature, flow rate, chemistry and land availability) and of available markets has been necessary (Lund, 2011).

In this paper we present the mapping of the ***shallow geothermal resource availability-SGRa*** (depth<1000 meters) and of the ***potential direct use-pDU,*** of an area located in the northern province of Rome (Central Italy) , between Tolfa Mountains (TM) and the western sector of Sabatini Volcanic District (SVD). The ***SGRa*** and ***pDU*** have been evaluated in terms of availability of natural hot fluids and suitable use. The fuzzy logic has been used for the evaluation of the SGRa. Whereas, for the pDU, a spatial analysis between availability of the resource and land use has been done. For this multidisciplinary approach, the use of dedicated Geographical Information System has been represented a powerful tool for the management of large spatial data sets.

2. GEOTHERMAL DIRECT USES IN ITALY

Italy is widely known for the strong expertise in field of geothermal production. Despite the presence of such industrial know how, previous analysis reveal a huge untapped potential in geothermal direct uses. Fortunately the current situation of direct uses of geothermal heat in Italy, compared with the situation of 2006, appear widely evolved, with an increase from 650 MWth and 8000 TJ to 850 MWth and 10000 TJ (Buonasorte, 2010). This increase is mainly due to the wide development of geothermal district heating and, in terms of numbers of installations, to single household applications which are widely applying heating & cooling equipment with geothermal source of small unit power (fig. 3). This has been recorded especially in the northern part of Italy despite the huge potentiality of the Central and South Italy.

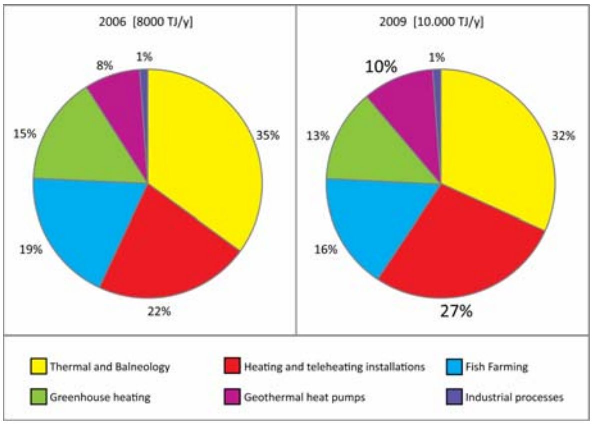

Figure 3: Italian Geothermal Energy by direct uses, in the period 2006- 2009 (modified from Buonasorte, 2010).

3. LOCATION AND DESCRIPTION OF THE STUDY AREA

The studied area is located in central Italy (Latium Region) in the northern province of Rome (41°54'39.24"N, 12°28'54.48"E), between TM and SVD, is surrounded to the south and north by hills, to the east by Apennines Chain and to the west by Tyrrhenian sea (fig. 4). Starting from late 60's until early 90's, geothermal exploration was performed in this area to identify geothermal resources for power generation.

3.1 Climate

The study area is located between Temperate and Mediterranean climatic regions (Blasi, 1999), the winter season is cold and is possible to have temperatures under 0°C, the number of months with mean temperature under 10°C is 3-4, the mean minimum temperature of the coldest month is from 0 to 6 °C and the mean annual temperature is from 12 to 16 °C (Blasi, 1999). Heating use is generally for 4-5 month/year and 10-12h/day (D.P.R., 1993).

3.2 Geology

The investigated area is extended from the western sector of the SVD to the town of Civitavecchia. From W to E, two different geological domains can be recognized (fig.4): 1) a sedimentary domain (Tolfa Flysch), constituted by Cretaceous-Oligocen flyschoid sediments and Miocene-Quaternary clay and sandy-clay deposits that crop out from TM to the Tyrrhenian Sea, and 2) a volcanic domain, formed by acid products of the Tuscan Magmatic Province and Quaternary undersaturated alkali-potassic volcanic rocks of the Roman Magmatic Province. The Tuscan volcanic products are found as dome complexes in the Tolfa (Tolfa Dome), Manziana and Sasso (Ceriti Dome) areas, whereas the Roman Magmatic products, mainly consisting of pyroclastic and phreatomagmatic deposits, centred on the Bracciano Lake and cover the entire region of the Sabatini Mountains (Di Girolamo, 1978; Peccerillo, 2005). The volcanic products overlie a sedimentary sequence that comprises, from bottom to top: 1) the thick Mesozoic carbonate formation that represents the main regional reservoir of Central Italy; 2) the Cretaceous-Oligocene Ligurian-type allochthonous flyschoid sediments (Tolfa Flysch) and 3) the Miocene-Quaternary neo-autochthonous clay and sand-clay formations

A large thermal anomaly characterizes the peri-Tyrrhenian sector of Central Italy, with heat flux values locally higher than 200 mW/m^2 (Cataldi, 1975) and a mean geothermal gradient of about 8°C/100m , likely associated with volcanic complexes and structural highs of the Mesozoic carbonates (Baldi, 1973; Ceccarelli 1987; Minissale, 1988). This thermal anomaly is related both to isotherms uprise joined to the extensional tectonic, and presence of the shallow magma bodies (Barberi, 1994). Moreover numerous thermal waters with temperature comprise form 21 °C to 52 °C are present (Baldi, 1973; Dall'Aglio, 1994; Duchi, 1995; Minissale, 1997; Frondini, 2008; Cinti, 2011).

3.3 Hydrogeology

The study area presents 5 main hydrogeological complex:

- Carbonate Complex: mesozoic limestone with high permeability.
- Volcanic Complex: SVD piroclastic deposits and laccolites (Tolfa, Cerite and Manziana Dome), characterized by medium-high permeability.

- Tolfa Flysch Complex: marly-sandy deposits with clayey alternations, characterized by low permeability.
- Continental Complex: travertines characterized by high permeability and slope and conoid deposits characterized by changeable permeability.
- Marine Complex: sandstones characterized by very low permeability with exclusion of the layers with particles size major than of the sand where there'a a medium permeability.

The main aquifers (fig.4) are related to: 1) a regional aquifer hosted in the thick sequence of Mesozoic limestones, and 2) shallow aquifer(s) hosted in the volcanic deposits (Capelli, 2005) and mean temperature of 16-18°C (Cinti, 2011). The depth of regional aquifer is between 200 metres and 3000 metres, the temperatures range from 80 °C to 260 °C (Cavarretta, 1987).

3.4 Fluid geochemistry data

The studied area is characterized by the presence of several thermal waters and gas emissions (Baldi, 1973; Dall'Aglio, 1994; Duchi, 1995; Minissale, 1997; Frondini, 2008; Cinti, 2011; Capelli, 2005;Cavarretta, 1987; Chiodini, 1999; Minissale, 2004) related to the central Italian thermalism, commonly attributed to the post-orogenic magmatic activity that occurred from Pliocene to Quaternary in response to tectonic movements associated with the opening of the Tyrrhenian Sea. The thermal springs (>21 °C) emerging in the SVD and TM have temperatures ranging from 21 to 52 °C, relatively high TDS values (up to 5000 mg/L) and Ca-SO_4 composition. This chemical composition is related to the main regional aquifer hosted within Mesozoic carbonates (Cinti et al., 2011). The highest temperatures are recorded at Stigliano (T=52°C) and Borgo Pantani (T=47°C).

3.5 Geothermal exploration and exploitation

Starting from late 1960s, geothermal exploration in large areas of southern Tuscany and Latium (Larderello-Travale field, Mt. Amiata volcano, Latera-Torre Alfina and Cesano fields) was performed by ENEL (National Electric Energy Agency) and AGIP (National Oil Company) (Cavarretta, 1987; Cataldi, 1973; Bertrami, 1984; Carella, 1985; Barelli, 2000), in order to quantify the potential resources suitable for electricity generation. Temperatures exceeding 300 °C were measured in deep geothermal wells at Larderello, Mt. Amiata and Latera at depth major than 3000 m [30]. During that period 24 deep wells and 61 test-holes were drilled in the SVD and TM, particularly in the Cesano area (eastern sector of the SVD), where temperatures up to 220 °C were measured at a depth of about 1500 m in brines with TDS (Total Dissolved Solids) up to 350 g/L (Barberi, 1994; Calamai, 1976; Funiciello, 1979). In the western sector of the SVD and in the TM, where most of the thermal discharges and gas emissions are located, the maximum temperature (290 °C) was measured in the SH2 well, at a depth of about 2500 m (Cavarretta, 1987). In the SVD and TM the attempts to produce electrical generation failed due to the environmental problems during the exploration.

Nowadays the utilization of the geothermal energy is rather poor and limited to very few installations: two spas at Stigliano and Ficoncella and a greenhouse at Borgo Pantani.

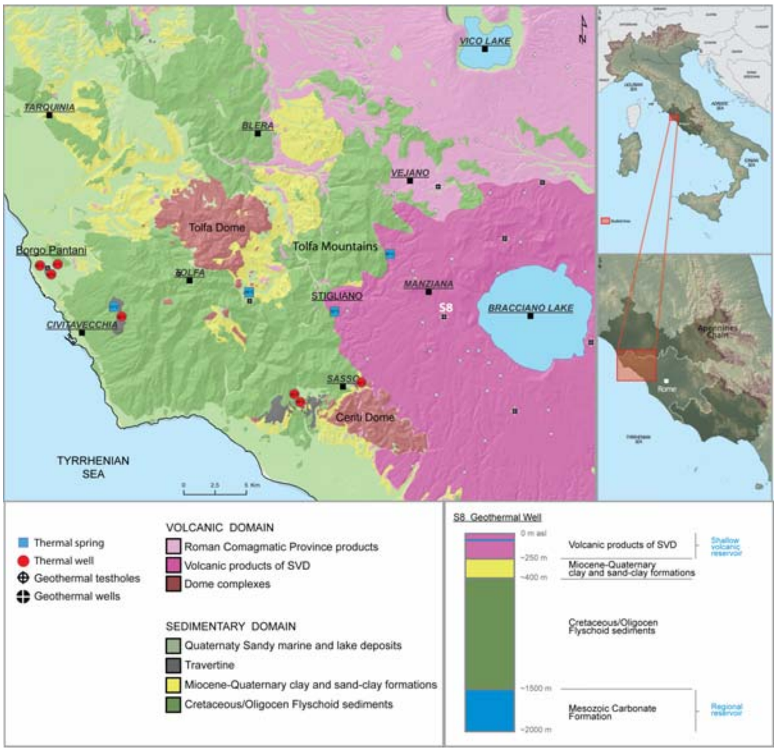

Figure 4: Location of the studied area showing the simplified geological map, the location of thermal waters, geothermal testholes and wells. It's also shown a simplified stratigraphic sequence from S8

4. METHODOLOGY AND DATA

In order to obtain a map of the “**potential direct use**” of the shallow geothermal resource, in terms of natural hot fluids use, is necessary to evaluate: i) the features of the resource, i.e. temperature, flow rate, chemistry, ii) the availability and iii) the land uses. The fuzzy logic and a dedicated geographic information system are the used tools. At first the main input data will be described.

4.1 Input Data

The data have been collected from public archives and papers and divided in two different types: underground data and surface data (Table 1).

Table 1: Input data

UNDERGROUND data	SURFACE data
- Depth of top regional reservoir	- DEM 20x20
- Temperature at top regional reservoir	- Land Use
	- Thermal Waters

4.1.1 Underground Data

The contours-maps (absolute heights above sea level) of depth and temperature at the top of potential regional reservoir, are freely available on the web site of Italian Economic Development Ministry (http://unmig.sviluppoeconomico.gov.it). The maps edited by ENEL during 80’s give information about the potential regional aquifer that represents the main geothermal reservoir. The vector and raster files relative to all described data have been created through ArcGIS software.

4.1.2 Surface Data

The digital elevation model (DEM) of the Latium region has been used to determine the absolute height of any surface data. It exists as a raster with a 20 x 20 m resolution. The information relative to land use are freely available on APAT web site (http://www.sinanet.isprambiente.it/it/strumenti/catalogo). These data give relevant information about main human activities, natural reserves and location of populated areas and main infrastructures. Physical-chemical features of groundwaters and thermal waters have been taken from Cinti (2011).

4.2 Methods

The ***SGRa*** and the ***pDU*** have been evaluated in terms of natural hot fluids availability and suitable use. For this purpose an evaluation of the features resource (temperature, flow rate, chemistry and land availability) and available “markets” has been necessary (Lund, 2011).

The fuzzy logic has been used for the evaluation of the SGRa, whereas for the evaluation of the pDU a GIS-Spatial Analysis between resource availability and land use has been done.

4.2.1 SGRa and Fuzzy Logic basics

In the last years several authors have been applying on models based on fuzzy logic Binaghi, 2003; Chung, 2001; Tahsin, 38; Boroushaki, 2010; Charabi, 2011; Gorsevski, 2003). It permits to solve many types of “real world” problems, especially when the system is difficult to model, is controlled by human operator, or where ambiguity or vagueness is common (Kahraman, 2010; Abouelnaga, 2009). Moreover it is applied often to energy planning and selection of energy resources (Kahraman, 2010; Abouelnaga, 2009; Kaya, 2010).

The fuzzy logic or theory, introduced by L. A. Zadeh (1965), facilities analysis of non-discrete natural processes or phenomena (Zimmermann, 1991). In the traditional logic, a set (A) is characterized by a membership function

$$M_A(x)$$

that assumes value = 1 inside of A or value = 0 outside of A. A fuzzy set, instead, has a membership function that assumes continuous values ranging between 0 and 1, then a generic element can belong partially ($0 \leq M_A(x) \leq 1$) to the set A. The membership function permits to evaluate, for each value, the membership degree, therefore it determines quantitatively how much the value belongs to a fuzzy set.

Fuzzy inference is an application of fuzzy logic that combines one or more variables in order to calculate an output variable depending on input ones by using a rule-based method (Mandami, 1976; Takagi, 1985). Main phases of fuzzy inference process are: *fuzzyfication* (transformation of input numerical variables into input fuzzy sets), *inference* (*if-then* rules application for the definition of output fuzzy sets) and *defuzzyfication* (transformation of output fuzzy sets into numerical output variable).

Fuzzy Inference model

Fuzzy Inference method has been applied in order to obtain a SGRa mapping. The analysis has been carried out in GIS-environment by using a fuzzy-tool specifically created for the present application. The tool, integrated into ESRI-ArcGIS software, executes fuzzyfication, inference and defuzzyfication phases that transform input physical variables into an output variable. The tool uses raster datasets for the input and output data. The analysis is focused on the selection of areas with depth of the reservoir top ≤1000 meters and useful temperatures for direct use of the resource (fig. 6). The independent input variables are:

- Depth of top regional reservoir (**D**)
- Temperature at top regional reservoir (**T**)

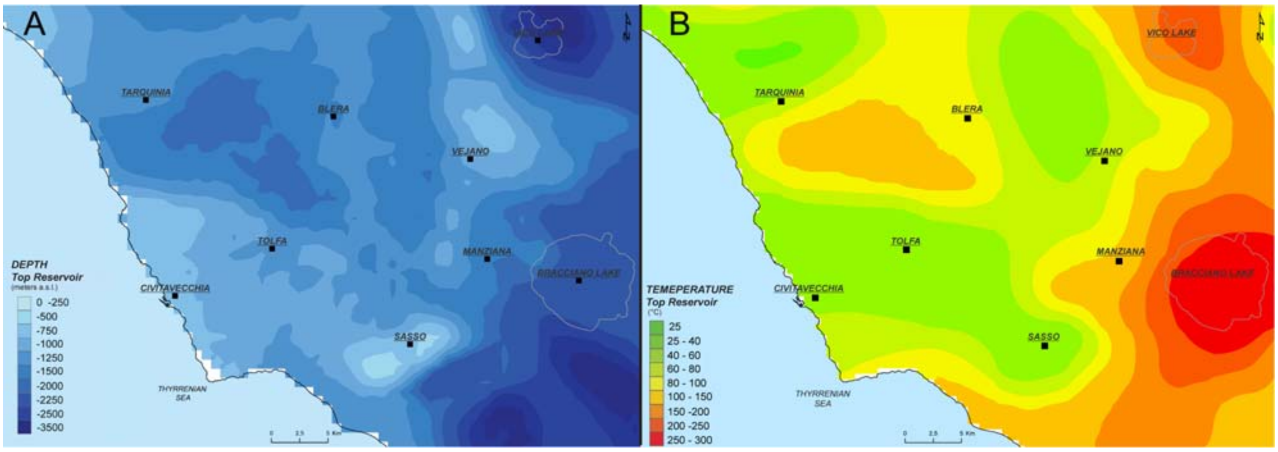

Figure 6: Depth (A) and temperature (B) at the top of reservoir (modified from http://unmig.sviluppoeconomico.gov.it and Cataldi, 1995).

The output, depending by input data (D-T), is an index ranging from 0 to 100, named "***geothermal index***", that quantify the availability of the shallow geothermal resource (i.e. SGRa).
The core of the analysis is the fuzzy inference model. This is a rule-based approach to calculate the general function *z=f(x,y)* from independent input variables (x and y) where the relationship among input and output variables is complex and non-linear. The fuzzy inference method follows the steps described below .

FUZZYFICATION. The cell-values of each input map (D-T), have been subdivided into five input fuzzy sets called: Very Low (VL); Low (L); Medium (M); High (H); Very High (VH). Fuzzy set names give a synthetic evaluation of the "***magnitude***" of the variable value.
A raster map has been calculated for each fuzzy set by using the fuzzy-tool in GIS-environment. At the end of the fuzzyfication phase we obtained 5 fuzzy sets for the input variable D and T (tab 2a-2b, 29; fig. 8).

Table 2a-2b: Fuzzyfication parameters of Top Reservoir Depth (D) and Top Reservoir Temperature (T).

Tab.2a	Xmin	Xc	Xc1	Xmax
VL	0	-	100	300
L	100	300	-	500
M	300	500	-	700
H	500	700	-	900
VH	700	-	900	1000

Tab.2b	Xmin	Xc	Xc1	Xmax
VL	0	-	25	40
L	25	40	-	60
M	40	60	-	80
H	60	80	-	150
VH	80	-	100	125

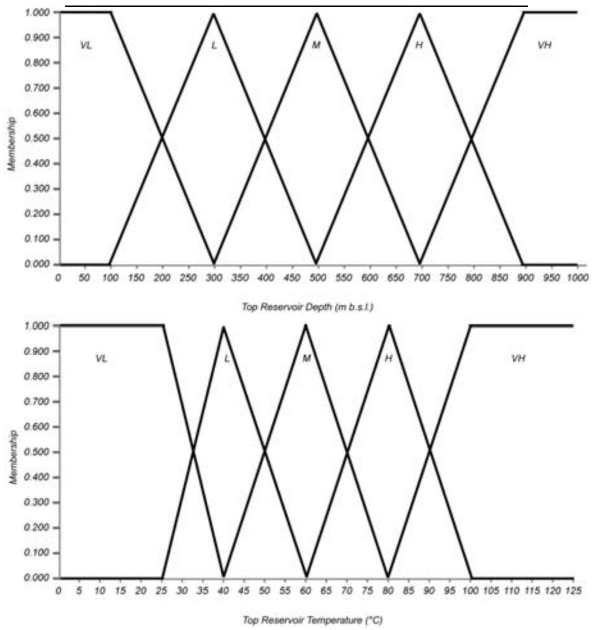

Figure 8. Linear membership functions. VL: very low. L: low. M: medium. H: high. VH: very high.

INFERENCE. It consists in the combination between top reservoir depth (D) fuzzy sets and top reservoir temperatures (T) fuzzy sets obtained by fuzzification analysis. Starting from 5 fuzzy sets for each input variable, 25 combinations are possible. Each combination "actives" a specific rule that establishes a resulting output fuzzy. The used ruled are shown in table 4.
The row header refers to the top reservoir depth (D) fuzzy set and the column header refers to the top reservoir temperatures (T) fuzzy set.
The collection of the rules is a list of *if-then* conditions that controls the result of the fuzzy inference. All possible combination between input fuzzy sets have

been taken into account, then 25 *if-then* conditions have been established.

Table 4: Rules table.

		T (°C)				
		VL (<30)	**L** (30-50)	**M** (50-70)	**H** (70-90)	**VH** (>90)
D (m)	**VL** (0-200)	L	H	VH	VH	VH
	L (200-400)	VL	M	H	VH	VH
	M (400-600)	VL	L	M	H	VH
	H (600-800)	VL	VL	L	M	H
	VH 800-1000)	VL	VL	L	L	M

Before the last phase (defuzzyfication) it is necessary to compose the output fuzzy sets an unique output fuzzy set. Accordingly with Kosko (1993), this operation has been carried out by calculating cell by cell the maximum values among maps representing the same set.

DEFUZZYFICATION. This is the final operation. During this phase, the output numerical value, named geothermal index, has been obtained (tab. 3).

Table 3: Fuzzyfication parameters for output fuzzy sets.

SGRa	Minimum	Central	Maximum	**GEOTHERMAL INDEX**
VL (Very Low)	-	0	25	**0-12.5**
L (Low)	0	25	50	**12.5-37.5**
M (Medium)	25	50	75	**37.5-62.5**
H (High)	50	75	100	**62.5-87.5**
VH (Very high)	75	100	-	**87.5-100**

The result is a map of the geothermal index, from 0 to 100, relative to the availability of the shallow geothermal resource (0 = not availability).

4.2.2 Potential direct use map (pDU)

The pDU map of the shallow geothermal resource has been carried out through an overlapping between resource and land use. The land use has been classified in 4 main classes: cultivated land, industrial area, urbanized area and woodland (tab.5). The woodlands has been cut off from the US because often these are natural protected areas. The analysis have been done in GIS environment.

Table 5: Land use classification.

CLASSES	**LAND USE**
1	cultivated land
2	industrial area
3	urbanized area
4	woodland

5. RESULTS

We developed a map of the sgra and pdu of that for the northern province of Rome (figg. 9-10). The resource availability is expressed in terms of *geothermal index* with values form 0 to 100 and six classes has been obtained:

- **Null**: any resource availability has been recognized because the depth of geothermal reservoir top (D) is major than 1000 meters;
- **Very Low**: geothermal index from 0 to 12.5; the underground properties are, D from 200 to 1000 meters and temperatures (T) less than 30°C; D between 600 - 1000 meters and T less than 50°C;
- **Low**: geothermal index from 12.5 to 37.5, D from 0 to 200 meters with T less than 30°C; D from 400 to 1000 meters coupled to T less than 50°C; D between 800 and 1000 meters with T less than 90°C;
- **Medium**: geothermal index from 37.5 to 62.5; D from 200 to 400 meters and T less than 50°C; D between 400 - 600 meters and T less than 70°C; D between 600 - 800 meters and T less than 90°C; D between 800 - 1000 meters and T major than 90°C;
- **High**: geothermal index from 62.5to 87.5; D from 0 to 200 meters and T less than 50°C; D between 200 - 400 meters and T less than 70°C; D between 400 and 600 meters and T less than 90°C; D between 600 and 800 meters and T major than 90°C;

  Very High: geothermal index from 87.5 to 100; D from 0 to 200 meters and T major than 50°C; D between 200 - 400 meters and T major than 70°C; D between 400 and 600 meters and T major than 90°C. The greatest SGRa is located along the coast, close to Blera town and along the NNW-SSE line from Manziana towards Vejano.

The figure 10 shows the map of the pDU of the resource. The land use classification, adopted for this analysis, highlights three main categories of potential application: cultivated lands, industrial areas and urbanized areas. The biggest industrial and urbanized areas are located along the cost close to Civitavecchia town but all over the study area the agriculture is the main activity. The main cultures are vegetables and flowers in greenhouse, vegetables in field, orchards, vineyards and olive tree groves. The woodlands has been excluded from the analysis because these are natural protected areas.

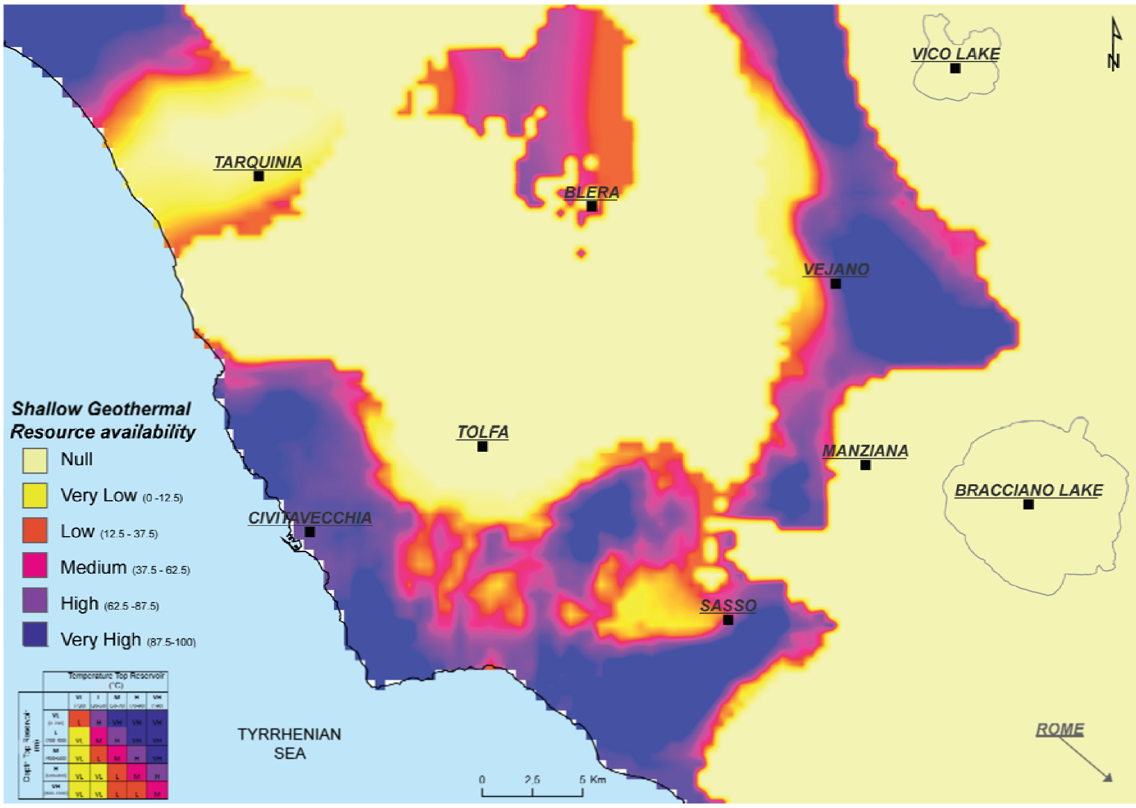

Figure 8: Map of the Shallow Geothermal Resource availability (SGRa) in the northern province of Rome.

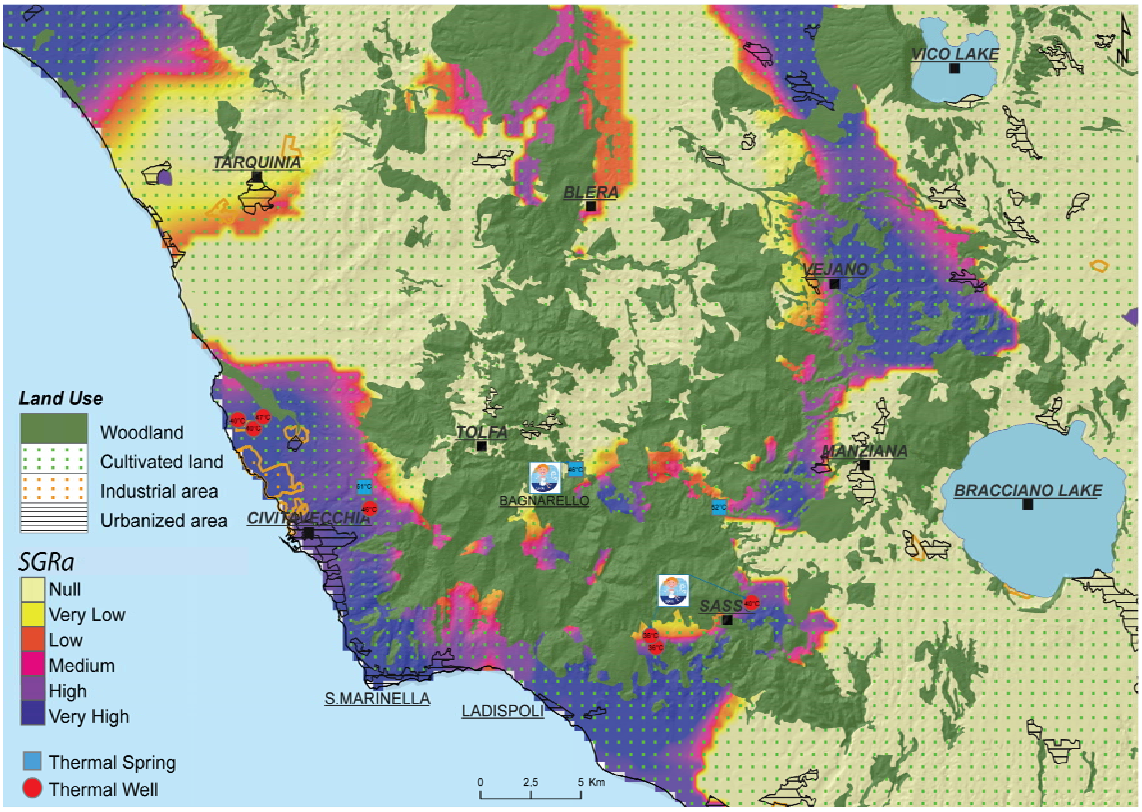

Figure 9: Map of the potential Direct Use (pDU) of the shallow geothermal resource in the northern province of Rome.

6. DISCUSSION

Several deep thermal anomalies are present in Central Italy, especially in Tuscany and Latium. The study area, located in the Latium region, in the northern province of Rome, could be an interesting sector for the use of the geothermal resource. The proposed map of the SGRa shows that the greatest availability is located along the coast, close to Blera town and along the NNW-SSE line from Manziana towards Vejano. The high *geothermal index* suggests the presence of top geothermal reservoir temperature major than 50°C and depth of that up to 600 m (a.s.l.). The geothermal reservoir is hosted in the Mesozoic carbonate formation, whereas the overlied formations such as Cretaceous-Oligocene Flysch, the Miocene-Quaternary neo-autochthonous clay and sand-clay formations and the volcanic products, represent the caprock. The Mesozoic carbonate formation is affected by a complex geological setting due to several subsidence episodes and a very intense extensional tectonic, starting from Miocene. The subsidence, mainly NW-SE trending, is concentrated in proximity of the Apennines while the Tyrrhenian side is characterized by smaller and less subsiding (Barberi, 1994). Therefore, the geothermal reservoir is shallower along the coast and on the western side of the Bracciano lake towards Tolfa. The temperature at the top of the geothermal reservoir increases in proximity of the volcanic domain where the geothermal reservoir is deeper than 1500 meters. Interesting temperatures at the top of the reservoir are also present along the coast, from Civitavecchia to Sasso town. For an indication of the potential direct uses of the shallow

geothermal resource, a map of that has been carried out. The direct using feasibility map shows that the agriculture is the most important land use. Therefore the geothermal resource, in terms of hot fluid, could be used principally in the agriculture for the field irrigation and for the greenhouse heating. The natural hot water could be also used in the farming, industrial processes and space heating of buildings. To this end, the teleheating could be developed along the coast, where several inhabited centers are present (Civitavecchia, S.Marinella and Ladispoli). Moreover, new spas could be developed in Sasso and Bagnarello, where thermal waters, with temperature from 36°C to 46°C are recognized.

The proposed maps can represent an useful tools to highlight convenient regions for shallow geothermal resource use. Moreover, these can give support to policy makers for decisions concerning increasing promotion of the geothermal resource use.

7. CONCLUSIONS

In Italy, despite the presence of an important geothermal industrial know how, previous analysis reveal a huge untapped potential in geothermal direct and indirect uses. This means that it's necessary to renew the interest for the geothermal energy. In this paper we proposed a mapping of the shallow geothermal resource availability-**SGRa** (depth<1000m) and potential direct use-pDU, for the northern province of Rome. This area has been interested by geothermal exploration during '60-'80 but despite the huge potentiality, no applications have been developed. Only two spas at Stigliano and Ficoncella and one greenhouse at Borgo Pantani are present.

The geothermal reservoir, hosted in the Mesozoic carbonate formation, is characterized by Ca-SO_4 water. The temperature of that increases in proximity of the volcanic domain, where the geothermal reservoir is deeper than 1500 meters. Interesting temperatures at the top of the geothermal reservoir are also present along the coast, from Civitavecchia to Sasso town. The SGRa has been carried out through the fuzzy logic. It permits to solve many types of "real world" problems, especially when the system is difficult to model, is controlled by human operator, there aren't many data, or where ambiguity or vagueness is common.

The results suggest that the greatest SGRa is located along the coast and on the line from Manziana towards Vejano, where the boundary between sedimentary and volcanic domain is present. Here the geothermal resource, in terms of hot fluids, could be used in the agriculture for the field irrigation and for the greenhouse space heating. The natural hot water could be also used in the industrial processes and space heating of buildings. Indeed, the teleheating could be developed in inhabited centers such as Civitavecchia, S.Marinella and Ladispoli. Moreover, new spas could be developed in Sasso and Bagnarello.

In some fields the study could be improved by more specific input data about deep geology and deep fluids geochemical composition data, but the proposed maps can represent a first step for the renewal of the interest about geothermics. Moreover, the maps can offer a planning support and marketing tool for the use of the shallow geothermal resource.

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