Spatial analysis and weighted overlay models as decision-making tools for geothermal resources exploration and exploitation: the Southern Italy case study

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ABSTRACT

Spatial analyses performed under GIS environments represent a powerful tool for environmental resources evaluations, to produce continuous thematic mapping of the territory as a function of interplaying factors.
The Purpose of this study was to establish spatial relationships among different kind of geological data throughout weighted overlay functions, in order to identify and map the Italian geothermal resource, focusing on its southern regions.
The approach to this challenging task was based on the differentiation of two main types of data which drive the research of a potentially exploitable geothermal resource: i) predisposing factors which basically allow the identification of a deep source of energy (namely an easy recoverable hot fluid); ii) limiting factors for its feasible exploitation, which essentially consist in geological hazards factors (mostly seismicity and seismogeneicity).
Data have been organized into a dedicated geo-database, including vector and raster information as: surface geology; principal faults databases (shallow and deep, active or not); seismogenetic sources and areas; gravimetric anomalies; stress maps and stress field regime analysis; underground information (wells and seismic profiles available from hydrocarbons and geothermal explorations); caprock and deep aquifers distribution; underground temperatures; heat flux; depths of potential reservoirs suitable to geothermal exploitation; recorded seismicity (INGV catalogues since 1981); historical seismicity; Italian seismic zonation; seismic hazard maps; volcanic hazard maps; principal diffuse degassing structures (DDS).
A series of transformations were performed in order to homogenize the layers information and to make the spatial correlation possible (mostly raster conversions and reclassifications). Biased weights were assigned to each reclassified layer value. Weighted Overlay operations were then conducted via the ArcGIS model builder tool, taking into account such weights and the overall influence of each layer. Two basic overlays of geo-predisposing factors and geo-hazards have been obtained. A final overlay between them was performed in order to produce the spatial distribution of the "reliably exploitable" geothermal macro-areas, which often correspond to the main geothermal manifestations already known. These also confirm the capability of this approach, which might be used to research new areas not clearly identifiable with the current datasets and classical approaches.
However, in such new areas more detailed "site-specific" studies should be performed to evaluate the geothermal potential in terms of thermal, electric power and energy supply.
This multidisciplinary approach would be proposed as a standard for the geothermal research evaluation and also extended to such researches aimed at the development of strategic energy mix plans in which different underground uses (CO_2 and CH_4 storage) can be combined with geothermal exploitation to solve the problem of the increasing energy demand.

1. INTRODUCTION

Geothermal energy exploitation is considered one of the most promising options for a future sustainable energy supply. The exploration for this resource has been performed since the early times of nineteenth century, especially in Italy. Despite the huge geothermal potential of Italian peri-Tyrrhenian areas (characterized by anomalous thermal gradients and high heat flux), only the two geothermal fields of Larderello-Travale-Radicondoli and Monte Amiata are presently exploited.
The classic approaches for the research of a potential geothermal resource pass through the initial recognition of superficial manifestations such as thermal springs and thermal anomalies (wells drilled for water use). In combination with these, several geophysical methods (some of which capable to highlight magnetic and gravimetric anomalies) have been always used as a major tool to identify the

underground structures, and to properly evaluate the presence of an accessible geothermal resource (namely a relatively shallow geological reservoir that hosts a hot fluid).
In this context the conventional geothermal exploration is generally conducted from a regional to sub-regional scale, (Goldstein, 1988; Wright et al., 1989), gradually focusing on the most promising areas, and proceeding with more detailed and site-specific studies (Dickson and Fanelli, 2004).
A new era of multi-scale and multi-disciplinary data analysis for the identification of underground resources is still developing, considering the capabilities of Geo-Information-Systems (GIS) spatial analysis tools. A combined analysis of several geo-information (such as surface geology, tectonics, composite well logs and seismic profiles data, underground temperatures distribution, magnetic and gravity fields, geochemistry) under GIS environment represents in fact a powerful contribution for the identification of underground resources.
Several authors already applied this methodological approach as a scheme for geothermal resources exploration (Noorollahi 2005, 2007; Coolbaugh, 2002, 2005a,b), evidencing that promising areas defined via GIS-based methods strongly correlate with such areas defined by conventional methods (Noorollahi 2007).
This work shows a review of the geothermal potential of Southern Italy, obtained throughout the GIS-based methodology proposed by Procesi et al. (this issue).
Results can be considered both as a case study for the validation of the methodology as wells as a new preliminary regional-scale geothermal exploration, to be subsequently refined with more detailed studies.
The innovation of this methodology is represented by the consideration of geological factors that help the identification of a geothermal resource together with others that may limit its realistic exploitation, namely the *Geo-Predisposing Factors* (GPF, e.g. thermal and natural gas manifestation, surface geology, tectonic setting, gravity measurements) and the *Geo-Hazard Factors* (GHF, mostly seismicity and volcanism), respectively.

2. METHODOLOGY

The workflow strategy consisted in a series of subsequent spatial operations and relationships established among the geo-information datasets.
Three main Feature Datasets were defined:

1) Input data
2) Processed data
3) Model data

2.1 Geo-database construction

The Input Data includes all the geo-information that have to be considered for spatial analysis and weighted overlay operations, organized into the two dedicated geodatabases of GPF and GHF (Fig. 2).

Input data have been acquired with the original formats: i) vector elements, which represent discrete/scattered territorial information as points (e.g. boreholes, thermal springs, etc), lines (e.g. faults, seismic profiles, etc) and polygons (e.g. seismogenic sources, restricted areas, volcanic ash fallout areas, etc); ii) raster or grid data for more widespread and continuous territorial information (underground temperatures maps, peak ground acceleration distributions, seismic zonation, etc).
It is important to stress that a general data inhomogeneity is observed along the whole Italian territory, especially for vector datasets.

2.2 Data Processing

The same geodatabase scheme used for input datasets has been also adopted for the Processed data feature dataset, which groups such grids obtained by the transformations of input data. Transformations of vector data into raster format were necessary to homogenize such information and to make possible further spatial analysis via GIS tools.

2.3 Weighted Overlay Procedures

A reclassification of the processed data has been performed to obtain the Model data.
Two ESRI ArcGIS® suite tools were used to build and run the spatial analysis model: the ModelBuilder tool and the Weighted Overlay functions.
Three weighted overlay models were designed into the ModelBuilder environment.

Model 1: identification of predisposing geothermal factors;
Model 2: identification of geo-hazard areal distribution;
Model 3: identification of potential areas suitable for geothermal exploitation.

These models were developed using several geo-processing functions (e.g. buffer, dissolve, density, weighted overlay). Weighted overlay functions were applied on the Model data.

3. DATA ELABORATIONS

The Weighted Overlay functions represent one of the most used approaches to solve multi-scale and multi-criteria spatial correlations under GIS environments, such as site selection and suitability models for natural resource evaluations.
Working data layers of this analysis (the Model data) were overlaid using a weighting system that reflects the influence of each layer in the overall geothermal potentiality evaluation process. Considering the range of variability of GPF and GHF data values, a restricted value (no-data) was used for areas to be excluded from the analysis. The final output model (Model 3) is a grid that represents the “favorability” of an area in terms of potential geothermal exploitation.

The process of Model data creation starting from input dataset is described below.

3.1 Input Data

Input data were collected from public archives and divided into main categories:

- *Geo-Predisposing Factors* (GPF)
- *Geo-Hazard Factors* (GHF)

3.1.1 Geo-Predisposing Factors (GPF)

- Tectonics

Active tectonics is considered to testify a potential shallow fracturing of the crust. Fractures and faults can play an important role in controlling fluid flow, as highlighted by several authors (Hanano, 2000; Blewitt et al., 2003; Noorollahi et al., 2007). In particular normal faults and extensional stress regime represent a promising condition for an easy recovering of a deep hot fluid. Back-arc domains such as the Italian peri-Tyrrhenian areas usually show these characteristics.
Stress regime information was extracted from the Italian Stress Map catalogue (Montone et al., 2012). Active faults distribution refers to ITHACA catalogue (http://sgi.isprambiente.it/geoportal/catalog/content/project/ithaca.page).
These catalogues contain a complete collection of present-day stress regime orientations and active faults along Italian territory, classified mostly under extensional, strike slip and compressive kinematics classes.

- Underground Data

High underground temperatures (> 200 °C) and relevant heat flux (> 60 mW/m^2) as well as a top reservoir depth lower than 2000 meters, and a high exploration density (number of wells and seismic profiles > 4/km^2) represent good conditions for a potential geothermal resource identification, also considering the economic convenience. The underground data were collected from Cataldi et al., 1995, Geothopica CNR catalogue (http://geothopica.igg.cnr.it/) and UNMIG database (http://unmig.sviluppoeconomico.gov.it), which include: underground temperature distributions along Italy (at 1000, 2000 and 3000 meters of depth); heat flux distribution; depth and temperatures of the potential geothermal reservoir top. The exploration density was computed under GIS spatial analysis tool as a processing of the number of available boreholes and seismic lines per square kilometer.

- Geochemistry

The geochemistry plays an important role in any investigation of geothermal resources, since it helps for the identification and characterization of thermal anomalies and fractured geological systems, especially when underground fluids circulation is present.
The geochemical data used in this work include the distribution of geothermal manifestations (as thermal spring, bubbling pools and fumaroles, Cataldi et al., 1995; http://geothopica.igg.cnr.it/) and hydrocarbon manifestation (mud volcanoes, gas seeps and oil seeps, Martinelli et al., 2012).

3.1.2 Geo-Hazard Factors (GHF)

Italy is located in an active geodynamical domain characterized by diffuse seismicity and active volcanism. The innovation proposed by this work with respect to classic approaches is to take also into account the distribution of the main geo-hazard factors, because those could limit or hamper a realistic long-term exploitation of a geothermal resource.

- Seismicity and Seismogenic sources

Several seismic catalogues were taken into account, including: the recorded seismic events from 1981 to 2012 (INGV CSI, http://csi.rm.ingv.it/, INGV ISIDE http://iside.rm.ingv.it/iside/standard/index.jsp); the historical seismicity from INGV CPTI catalogue (http://emidius.mi.ingv.it/CPTI11/); the seismogenic sources distribution (INGV DISS Database, Basili et al., 2008, http://diss.rm.ingv.it/diss/), the seismic zonation (INGV joined to DPC project, http://www.protezionecivile.gov.it/jcms/it/classificazione.wp) and the expected peak ground acceleration (PGA) map, treated as the seismic hazard map of Italy (http://zonesismiche.mi.ingv.it/).
Recorded seismicity was considered to estimate the events density and the magnitude distributions along the Italian territory.
The DISS Database shows the distribution of Individual (IS) and Composite (CS) seismogenic sources, namely the 2D projection of structures (IS), or envelopes of these (CS) which could potentially generate a certain type of seismic occurrence.
The Seismic Zonation was considered as the seismic classification of the Italian municipalities in 4 classes, depending on the probability for an area to be affected, in a certain time interval (generally 50 years), by a seismic event exceeding a fixed magnitude threshold. Zone 1 includes all areas where strong earthquakes can occur, while zone 4 describes areas having less probability of occurrence.
The seismic hazard map of Italy shows the distribution of maximum peak ground acceleration (PGA) with the 10% of exceedance probability in 50 years.

- Active Volcanism

Several volcanic districts are present in Italy, but the active complexes are mostly located in the southern part, along the peri-Tyrrhenian area. The active volcanism of southern Italy is characterized by explosive (as Vesuvius) and effusive (as Etna) behavior, and it could represent a geological hazard factor for a suitable geothermal exploitation. Even if active volcanic areas represent the sites of major temperatures at depth, the exploitation of geothermal energy there might be more costly and risky for the long-term strategy of the whole process. Areas subjected to primary (lava/surge) or secondary flows (lahar), or with an expected excessive amount of ash fallouts within a certain (or at least short) recurrence

time, should be carefully treated during geothermal resources investigations.
Active volcanism areas were extracted by De Natale et al., 2006 for the Vesuvius area, Rossano et al., 2004 for Phlegrean area and Damiani et al., 2006 for Etna Area.

A summary of GPF and GHF input data is shown in Fig. 1.

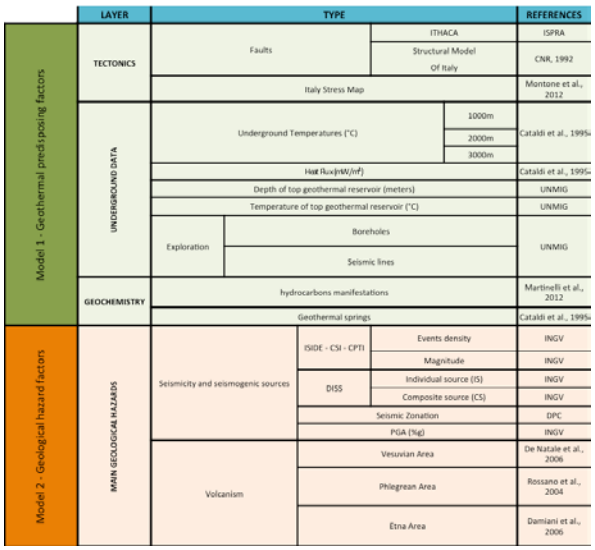


Figure 1: Input data divided into GPF and GHF classes

3.2 Processed Data

The input data were processed throughout a series of transformations, in order to homogenize the territorial information and to make possible further spatial correlations. The first step was the creation of a workspace grid constituted by more than 1.45M cells (1x1 km), in order to cover the whole Italian territory.
The main performed transformations are:

- Conversion from vector to grid;
- Spatial references homogenization;
- Definition of the grid classes;
- Reclassification of the grid classes.

Several grids were obtained. For each grid two or four classes were defined grouping ranges of values, and then reclassified assigning a digital value from 1 to 4 to each class. This reclassification was necessary in order to allow further overlay calculations.
The value **1** was assigned to such classes that define the most favorable conditions for the geothermal exploitation (presence of an exploitable deep resource or low hazard factor concentration). Consequently the **2**, **3** and **4** values were assigned to less and less promising conditions (e.g. limited underground information or high GHF concentration).
No-data class was assigned to layers cells with non-homogeneous territorial data coverage. This type of class is considered non-favorable for the GPF while favorable for the GHF.

3.3 Model Data

In order to produce comparable datasets for the *Weighted Overlay* procedures (the model data), a *weight* (numerical code) was assigned to each reclassified class. Weights of each layer classes have been defined considering how much the presence of such information in a certain portion of the territory could improve the identification and the quantification of the resource (GPF) or eventually limit its effective exploitation (GHF).
The weights range between 1 and 9. High values (e.g. 6-9) refer to favorable conditions for the geothermal exploitation, for both GPF and GHF.
Therefore, low values for the GHF mean high concentration of adverse conditions (namely geo-hazards) for a reliable geothermal exploitation.

4. WEIGHTED OVERLAY WORKFLOW

After data homogenization and processing, the Weighted Overlay operations were conducted under the ESRI ArcGIS Model Builder environment. The workflow scheme (from input data gathering to the overlay modeling) is shown in Fig. 2.
Models were calculated considering the reclassified values, the classes weights and the overall layer *influence*, for each cell in the workspace.
The underground distribution of temperatures, the boreholes, the seismic profiles data, the active volcanism, the seismic events, seismic zonation and the PGA distributions were considered as carrying the spatial information with the major percentage *influence*.
For the GPF, the presence of a thermal spring, a normal fault in a pure extensional regime area as well as a reservoir set at shallow depth with high underground temperatures produce layer cells with high-ranking values, with the corresponding high class weights to be considered in the overlay functions.
Conversely, for GHF, the concentration of seismicity, seismogeneicity as well as volcanic hazard in a certain area produces an output overlay cells with low-ranking values, with the corresponding low class weights.
Two basic overlays models of the GPF (MODEL1, Fig. 3) and the GHF (MODEL2, Fig .4) were computed. The analytical procedures of the overlay algorithms were resumed in Fig. 2.
A final overlay between them was performed to produce the spatial distribution of the “reliably exploitable” geothermal macro-areas, the GPA (MODEL3, Fig. 5). The influence of MODEL1 and MODEL2 in the final weighted overlay was set as equal (50%).

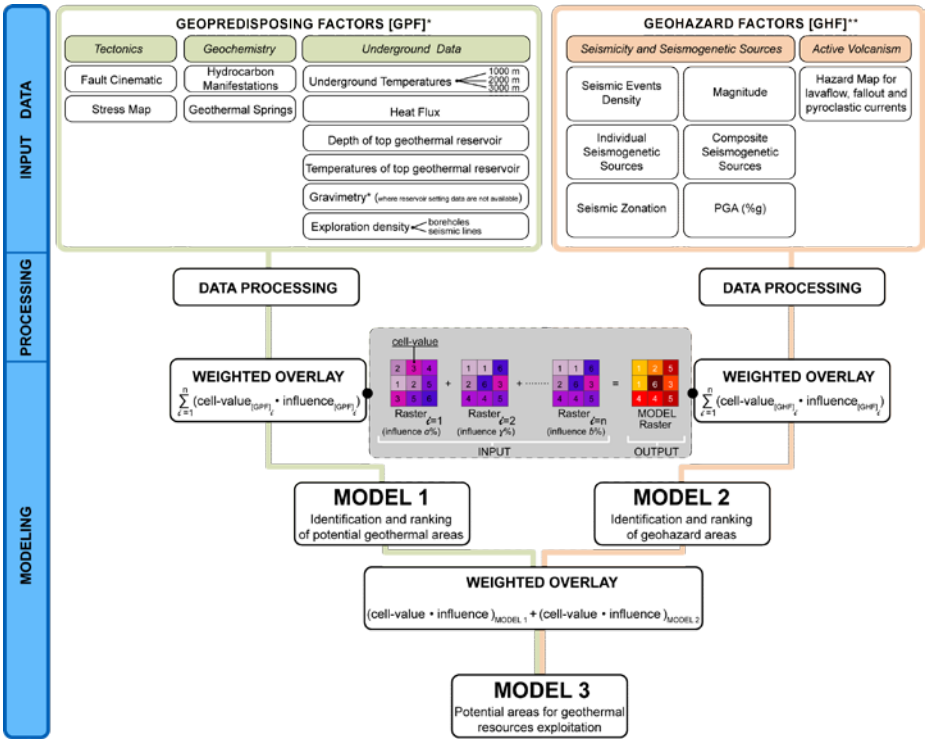


Figure 2: Workflow for input dataset organization, data processing and overlay modeling.

5. RESULTS & DISCUSSIONS

Generally the result of a weighted overlay computation is a grid layer. The grid cells obtained with the overlay models can acquire values from 1 to 9, as reflecting low ranking to high-ranking classes, respectively. The final overlay result (Model 3) represents a map of long-term reliably exploitable geothermal resources, even in relatively low-data coverage areas.

5.1 Model 1 – *GPF for geothermal resource identification*

The results of Model 1 show the areas where the geo-predisposing factors for geothermal resource identification are more concentrated.
The weighted overlay classes can range from 1 to 9 values. Low values (from 1 to 5) testify a low input data density or the absence of a potential geothermal resource. Conversely high values (from 6 to 9) indicate high data concentration and the presence of a potential geothermal resource.
It is necessary to underline that the result of this analysis is strictly conditioned by the input data distribution and data interpolation procedures.
Results show a good correlation between the clustering of predisposing factors and the known geothermal anomaly areas of southern Italy, and active volcanic centers (Fig. 3). Even if Model 1 highlights the presence and the extension of potential deep geothermal resources, a feasible use of those necessarily passes through the evaluation of the geological hazards present in those areas.

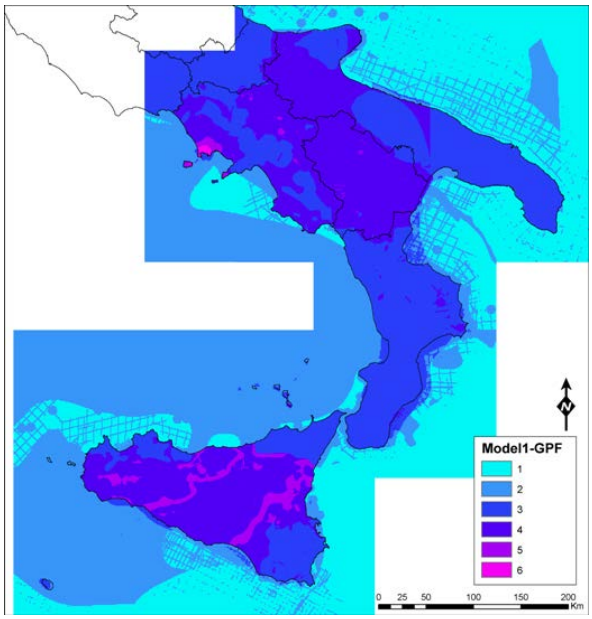


Figure 3: weighted overlay map of the geo-predisposing factors (GPF).

5.2 Model 2 – *GHF for geohazards identification*

Results of Model 2 show the areas where the main geo-hazard factors are more concentrated.
Also in this Model the weighted overlay classes values have a range from 1 to 9. No-Data or Low values

(form 1 to 5) testify a high geological hazards concentration, condition that could limit or hamper the long-term exploitation of a geothermal resource. Conversely high values (from 6 to 9) witness for low hazard density, a favorable condition.
As well as for Model 1, the results of this analysis are strictly conditioned by the input data distribution and data interpolation procedures.
Principal clustering of geo-hazard can be localized close to the main active volcanic centers and along Apennines and Calabrian chains, where the seismicity and the seismogenetic sources are recognized (Fig. 4).

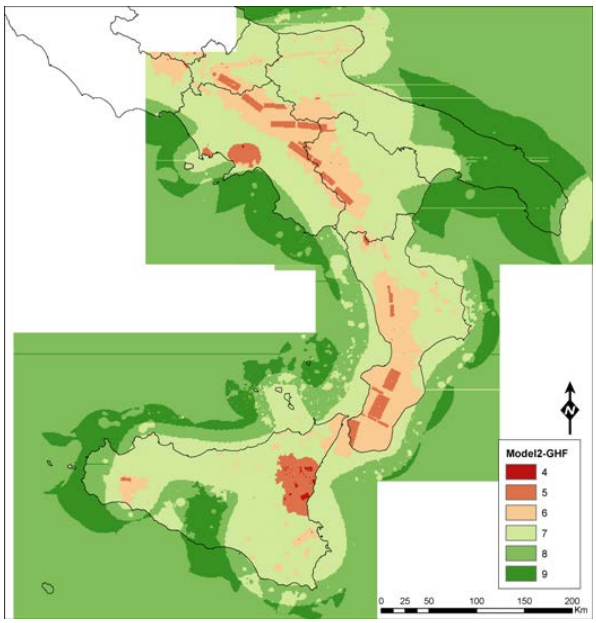


Figure 4: weighted overlay map of the geo-hazard factors (GPF).

5.3 Model 3 – *potential areas for a reliable geothermal resource exploitation*

A final overlay procedure between Model 1 and Model 2 was performed in order to identify the areas where the evidence of a potential geothermal resource is combined with low geo-hazard concentration. Such areas could be considered for long-term and more reliable geothermal resource exploitation, namely the economically feasible recovery of a hot fluid source within 3 km of depth, in a relatively "stable" environemnts.

As the previous models, weighted overlay classes of Model 3 range from 1 to 9. Low values (form 1 to 5) testify a low potential exploitation of the geothermal resources whereas high values (form 6 to 9) witness for a high potential. More in detail the values 8 and 9 indicate such areas where the geothermal exploitation can be a realistic option. Cell values from 5 to 7 can be considered as sites where a further data acquisition can better constraint the knowledge of underground setting as well as the geothermal resource, especially if located in hazard areas. Cell values below 5 testify the absence of a resource and/or a huge concentration of geo-hazards, or alternatively a substantial absence of underground data.
Model 3 did not calculate high-ranking values for Southern Italy, since most promising areas fall between 5 and 7 classes. This means that potential resources and particularly the geohazards are present influencing the calculation, or alternatively that further data acquisition and site-specific analysis should be performed there to improve the general knowledge of the underground resource as well as the limiting factors.
The more promising areas highlighted by Model 3 are located in Campania active volcanism areas and in Sicily (Fig. 5).
This methodology evidences also the presence of small promising areas (mostly located within the Apennine chain), not yet completely highlighted by previous works or prior literature knowledge.
As already evidenced by Model 1, the high-ranking areas of the Model 3 are in a good correlation with the distribution of existing geothermal anomaly areas. This also demonstrates that the proposed methodological approach is valid and can be considered as reliable.
It is important to point out that Site-specific analyses should be however performed in such areas identified with the proposed methodology, both to quantify the geothermal potential of the resource and to plan a more realistic exploitation.
We strongly feel that this kind of multidisciplinary and regional approaches can represent the first step to be followed in a geothermal exploration program.
This kind of works also represent an important opportunity to link the scientific community and the decision-makers, politicians and stakeholders, giving them a concrete tool to develop strategic energy plans.

6. CONCLUSIONS

A geothermal exploration program requires the combined analysis of a various sets of geo-information, including surface geology, tectonic setting, underground temperature distribution, heat flux, boreholes and seismic profiles data, geochemistry as well as geomagnetic and gravity measurements, if available.
The Geographic Information Systems (GIS) applied to this target represent a powerful tool to manage such kind of different dataset, with a multi-scale and multi-disciplinary approach.
A series of spatial analysis functions permit the correlation of several geo-information, to better evidence promising situation not directly detectable with the use of classic approaches.
We used a GIS-based methodological approach to review the geothermal potential of Southern Italy.
Efforts of this analysis were based on the consideration of two main types of geological data: Geo-Predisposing Factors (GPF), namely the favorable geological factors for geothermal resource identification (e.g. thermal and natural gas

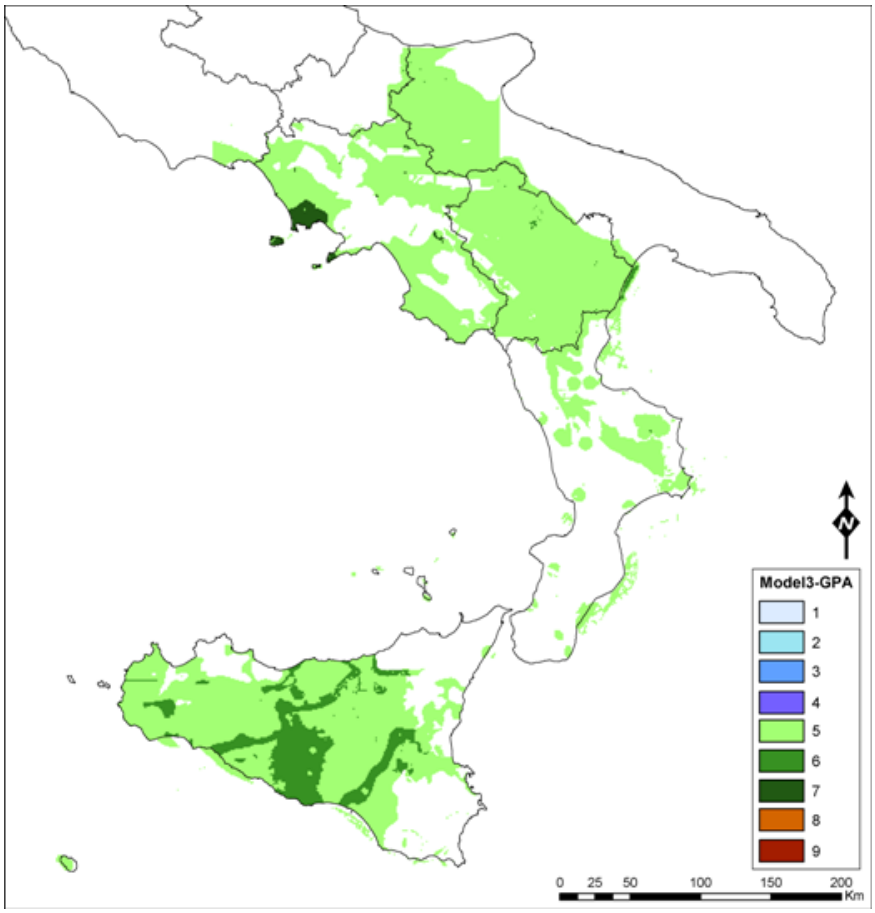


Figure 5: weighted overlay Map of the Potential southern Italy areas suitable for geothermal exploitation (GPA), as a result of the proposed methodological approach. Most promising areas fall between 5 and 7 classes, which means that both potential resources and geohazards are present, and further data acquisition and site-specific analysis can improve the general knowledge of the underground resource.

manifestations, surface geology, tectonic setting, gravity measurements) and Geo-Hazard Factors (GHF), namely such geological hazard which could potentially limit the long-term exploitation of a geothermal field (e.g. seismicity and volcanism).Input data were organized into a *Geodatabase* and processed throughout a series of spatial transformations, which homogenized and extrapolate as much as possible the vector data on the territory. Those operations were necessary since spatial overlays need to be performed between raster datasets formats.

Two main tools were then used to design and run the spatial analysis model: the *ModelBuilder* tool and the *Weighted Overlay* functions.

Aim of this workflow is to validate itself identifying the already known geothermal areas without a-priori geological information, and to evidence further promising geothermal areas not detectable with the usual approaches.

Two basic weighted overlay models of the GPF (MODEL 1) and the GHF (MODEL 2) were computed.

A final overlay between them was performed to produce the spatial distribution of the "reliably exploitable" geothermal macro-areas (GPA, MODEL 3).

Results show a good correlation between the high-ranking areas of the Model 3 and the distribution of the already known geothermal anomalies present on the territory. This demonstrates that the proposed methodological approach is validated and can be considered reliable. This methodology also evidences the presence of new promising areas, not yet completely defined by previous works or prior literature knowledge.

We strongly feel that this new methodological approach may be used as first appraisal phase for the research of new geothermal resources, both in unexplored areas and in places where active geothermal fields are still working.

The research of new potential resources represents in fact an important issue in the framework of the sustainable development of renewable energies.

Moreover, this kind of works represent an important opportunity to link the scientific community and the decision-makers, politicians and stakeholders, giving them a concrete tool to develop strategic energy plans.

Anyway, more detailed and "site-specific" studies should be performed in the areas identified by the proposed methodology, in order to evaluate the reliable geothermal potential in terms of thermal power, electric power and energy supply.

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