Assessment and Mapping of Radon-prone Areas on a regional scale as application of a Hierarchical Adaptive and Multi-scale Approach for the Environmental Planning. Case Study of Campania Region, Southern Italy.

DOMENICO GUIDA [(1)*], MICHELE GUIDA [(2, 4)**], ALBINA CUOMO [(1)],
DAVIDE GUADAGNUOLO [(2)], VINCENZO SIERVO [(3)]
[(1)]Department of Civil Engineering, University of Salerno, Via Ponte don Melillo, 84084 Fisciano (SA), ITALY,
[(2)]Department of Physics, University of Salerno, Via Ponte don Melillo, 84084 Fisciano (SA), ITALY.
[(3)]C.U.G.RI., interUniversity Centre for Applied Research on the Prediction and Prevention of Major Hazards, University of Salerno, Via Ponte don Melillo, 84084 Fisciano (SA), ITALY.
[(4)]I.N.F.N., National Institute for Nuclear and Subnuclear Research, Salerno Branch, University of Salerno, Via Ponte don Melillo, 84084 Fisciano (SA), ITALY.
* dguida@unisa.it, ** miguida@unisa.it

Abstract: - Nowadays, it is well established, among the international scientific community, that inside dwellings the largest contribution to the indoor Radon levels is provided by the source of the exhalated Radon, produced both directly from the soil located underneath the buildings and from the neighbour soils. This shared awareness has induced many European public institutions, responsible in matter of public health, to issue directives aimed at the assessment of the potential Radon exhalation from the soils, at regional scale, in order to achieve a planning of the radiogenic risk both in the residential buildings and in the working places. However, on one side, the lack of consolidated methodologies and procedures, shared among the experts' community, has produced a valuable intense investigation research activity; on the other one, it led to the developing of different procedures, starting from diversified approaches. Synthetically, they can be classified according to the following typologies: i) indoor Radon measurements campaign-based approaches, ii) geology-based and geology-indoor correlation based, and iii) integrated ones. On the base of this last approach, the authors have started an interdisciplinary research program with contributions from Geology, Geomorphology, Soil Science, Environmental Physics, Building Engineering and Radiology and Epidemiology aimed to the development of a standard methodology, based on a multi-scale hierarchical (regional - provincial - sector- zone site) procedure of assessment of the Radon exhalation from soils. Such a procedure exploits an integrated, adaptive, approach to the problem as it requires the use of techniques of analysis, which are differentiated at the different scales of the territorial surveys and analysis. At the same time, they are interactive and progressively more deepened and more specific, from the regional to the zone mapping and modelling at the scale of a single site. The research is supported by a built-in database about Campania Region, consisting of both suitable territorial informations and experimental data provided by Radon activity concentration measurements in soil-gas performed in several sites and indoor measurements, integrated in a GIS-based management procedure. For its properties, this interdisciplinary multiscalar hierarchical adaptive approach can be successfully applied in many environmental studies and analysis.
An interdisciplinary hierarchical multiscalar and adaptive methodology like the one described in this paper turns out to be a very powerful tool in many environmental and territorial planning approaches, especially wherever a "vast area" approach is needed to the environmental issues, i.e., the case of the urban acoustical or the electromagnetic pollution zoning. The "vast area" is an emerging concept and it regards a systemic approach to urban and regional planning methodology of analysis, design and management. Integration is pursued between the contributions given by the various disciplines involved in the planning process.

Key-Words: Environmental Planning, Environmental Radioactivity, Radon Prone-Areas, Radon soil-gas, GIS maps

1 Introduction

Recent studies have confirmed the lethal effects of Radon to human health [1]. Above all, the studies on the risk of lung cancer has concluded that there is a strong evidence of an association between the exposure to indoor Radon concentrations and lung cancer. Moreover, indoor Radon accounts for about 9% of deaths from lung cancer and about 2% of all deaths from cancer in Europe [2]. Therefore, detection of the areas with higher concentrations in outdoor-indoor Radon is essential for assessment and prevention of the risks to the human health [3].
The prevalent source of high indoor Radon (in house air Radon concentrations) is the Radon-soil gas produced by emanation from the rock fragments or crystals and exhalation from pore spaces in the soil [4]. Therefore, field studies [5-11] have proved that a strong relation exists between geology and Radon-soil gas. Consequently, the Radon potential for a given region is likely to be the result of combinations between the properties of the underlying rocks, as the distribution of Uranium and Radium and those ones of the soil, as thickness, porosity, permeability, and moisture content. Therefore, realization of Radon-soil gas maps would be extremely useful for professionals and municipality officials in planning and management practices.
In the European countries, different approaches for the survey techniques, classification systems and mapping procedures of the Radon potential exist, e.g. the indoor Radon in United Kingdom [12] and Switzerland [13], the Radon-soil gas in the Czech Republic [14, 15] and Germany [16].
In Italy, the PERS project (Exhalation Potential of Radon from Soil), proposed an "*a priori*" approach, based on the main geological factors affecting the emanation and the exhalation process in the Radon-soil gas production. The PERS Project has been extensively applied and experimentally verified both in the Region of Veneto and the Autonomous Province of Bolzano [17].
Referring to the last approach, the authors have started our own approach based on a vast area methodology based on an interdisciplinary research program with contributions of Geology, Geomorphology, Pedology, Hydrogeology, Environmental Physics and Building Engineering. The aim of the program is to develop a standard methodology suitable for the Radon-soil gas assessment at the regional scale level, in particular for the case study of the region of Campania, and construct a GIS-based representation of a map of the Radon Hazard (containing the distribution of the so-called Radon-prone areas). Likewise the Seismic Hazard and the Volcanic Hazard Maps, the Hydrogeological Hazard Maps, also the Radon Hazard Map will provide a precious tool for the future urban and environmental planning and besides that will constitute a powerful territorial decision support tool to optimize the successive epidemiologic investigations.
The methodology is applied in hierarchical and multi-scale analysis, progressively more deepened and specific in detailed spatial scale: coarse zoning at the regional scale, fine zoning at the provincial scale, field measurement at district and zone scale, and modelling at the site study level. The field and indoor measurements are performed using both an active portable instrumentation for the alpha spectrometry of Radon short-lived progenies (the Radon Monitor RAD7 with an AMS Soil Gas Probe - Durridge Co., USA) and the passive instrumentation Rad Elec E-PERM system (Electret-Passive Environmental Radon Monitor).
A Radon Potential Map of Campania region, based on bibliographical correlations, is firstly performed at the scale 1:250,000. Successively, at the province level, geology-based correlations and aimed field measurements, both managed in GIS procedure, enable to define the Radon-prone areas Map of the Salerno Province, represented at the scale 1:100,000. Finally, at the District level, the correlations between Radon-soil gas field measurement and the detailed stratigraphic data from pre-existing boreholes serve to perform the zoning in the Alto Irno-Solofrana areas, resulting as one of the higher concentrations in potential Radon-soil gas at province scale analysis level. Suitability of the methodology in Radon potential analysis at municipality scale is also shown.
An interdisciplinary hierarchical multiscalar and adaptive methodology like the one described in this paper turns out to be a very powerful tool in many environmental and territorial planning approaches, especially wherever a "vast area" approach is needed to the environmental issues, i.e., the case of the urban acoustical or the electromagnetic pollution zoning. In fact, a suitable acoustical propagation modelling and noise mapping is relevant for local areas, as exploited in [18] for a wind turbines or in [19, 20] for road traffic noise. The "vast area" is an emerging concept and it regards a systemic approach to urban and regional planning methodology of analysis, design and management. Integration is pursued between the contributions given by the various disciplines involved in the planning process. According to this approach in Italy the concept of urban planning and

territorial planning has been converted into the one of territorial governance, adopted by the Italian Constitution and by recent regional legislation.

2 About Radon

2.1 Radon: basic physical and chemical properties

Radon-222 (^{222}Rn), afterwards named simply Radon, was discovered in 1898 by Friedrich Ernst Dorn, as the third radioactive element, after Radium and Polonium [21]. It is a naturally occurring radionuclide with a half-life of about 3.8 days, decaying in several isotopes (26), only two of them can be classified as naturally occurring substances: Thoron (^{220}Rn) and Actinon (^{219}Rn). Radon is Radium-226's direct progeny (^{226}Ra, half-life of about 1600 years) and it occurs in the natural isotopic decay chain (Fig. 1), whose progenitor, Uranium-238 (^{238}U) (half-life of about 4,5 billions of years), is almost ubiquitous, i.e., one of the most diffused, and naturally occurring radio-elements in the Earth's crust – 3 p.p.m. on the average [22].

Unlike the other radioisotopes occurring in the Uranium decay series, Radon is the only gaseous element at normal conditions of temperature and pressure. Moreover, it turns itself out to be, also, unstable, as it decays in a solid short-lived progeny, like Polonium-218 (^{218}Po) and Polonium-214 (^{214}Po), both of outstanding relevance from the point of view of the radioprotection of the exposed workers and population, as they deliver radiologically significant dose to the respiratory epithelium [23]. For what it concerns its chemical properties, Radon belongs to the VIII group of the Periodic Table and, therefore, it is a noble, colourless, odourless, tasteless and, almost, inert gas. But, conversely from the other noble gases, it turns out to be the heaviest among them and characterized by the highest values of the boiling and the melting points, and the critical parameters, like temperature and pressure.

2.2 Radon: sources, measure unit, behaviour and health effects

In the natural environments the main source of Radon is provided by soils (*Radon-soil gas*), where it is produced from the ^{226}Ra decay inside the grains of rocks, according to the so-called "emanation process" [4, 24]. In the International System (SI), the unit of radioactivity of the Radon is the *becquerel* (symbol Bq), defined as the activity of a quantity of radioactive material in which one nucleus decays per second. When measuring radioactivity of a sample with a detector, a unit of "counts per second" (cps) or "counts per minute" (cpm) is often used. These units can be converted to the absolute activity of the sample in Bq if one applies a number of significant conversions, e.g., for the radiation background, for the detector efficiency, for the counting geometry, for self-absorption of the radiation in the sample.

From soils it can be freed through the "exhalation process" into the atmosphere; here, it is dispersed by the air flows (*Radon-in-air*), reaching, generally, only low values of concentration – typically around 5-10 Bq/m^3 [23]. Instead, in the confined environments, like houses and working places, it accumulates (*indoor Radon*) and reaches, even, high levels of concentration, due to the fact of being almost 7 times heavier than air. The concentrations both in Radon-soil gas and in air Radon are measured in Bq/m^3.

The main physical cause of Radon entry into a confined space is associated to the occurrence of a pressure gradient between the interior and the exterior of a dwelling and also to the presence of cracks and fractures in the foundation structures, wall-floor joints and pipes, which are preferred ways for Radon to entry into the confined spaces.

It has been demonstrated that the sources of Radon penetration into buildings are: foundation or embankment soils (main source), and, with a much lower contribution, drinking and sanitary water and building materials [25].

Since 1988, World Health Organization (WHO) has established that inside confined spaces the exposure of population to Radon can turn out to be the second risk factor of lung cancer, after cigarettes smoking, classifying it, therefore, as cancerogenic agents into the Group I, i. e., substances with a well-known oncogenicity. In fact, due to its ubiquitous presence in the air, it can be inhaled and, in large part, breathed out by people exposed to it. Furthermore, on the contrary, its "short-lived" decay products, 218Po and 214Po, solid and electrically charged, can bind themselves "electrostatically" to the aerosols present in confined environments, and be retained into the bronchi, after inhalation. The radiation released during the subsequent decay of the alpha-emitting decay products, 218Po and 214Po, delivers a radiologically significant dose to the respiratory epithelium, producing a damage to the DNA of the lung tissues, because of the high energy released to them by the α particles emitted. A large part of these biological damages is “repaired” by appropriate cellular mechanisms, while the non-repaired one can, with time, turn into cancer [26]. In the latest decades different models for evaluating the increase of lung cancer risk versus the Radon concentrations exposure have been developed [27-29], with the result that from them clear evidence of a linear correlation between risk and exposure can be undoubtedly obtained. In Italy, also, the relevance of the exposure to Radon has been, carefully, considered by the Ministry of Health in the framework of the so-called National Health Plan (1998-2000). In this plan it has been estimated that the incidence of lung tumours, attributable to Radon, is quantifiable, in comparison to the number of cases of same kind of tumours induced by other causes, with a percentage value comprised in the range 5-20% [30]. Consequently, as in our country each year an average of 36,000 cases of lung cancers are recorded, according to the above estimation, the Radon can be considered responsible of about 1800-7200 disease cases every year. For what it concerns other possible health effects, the results of some oncologic studies have indicated a possible correlation, not yet confirmed, between Radon exposure and some kinds of leukaemia and tumours [29].

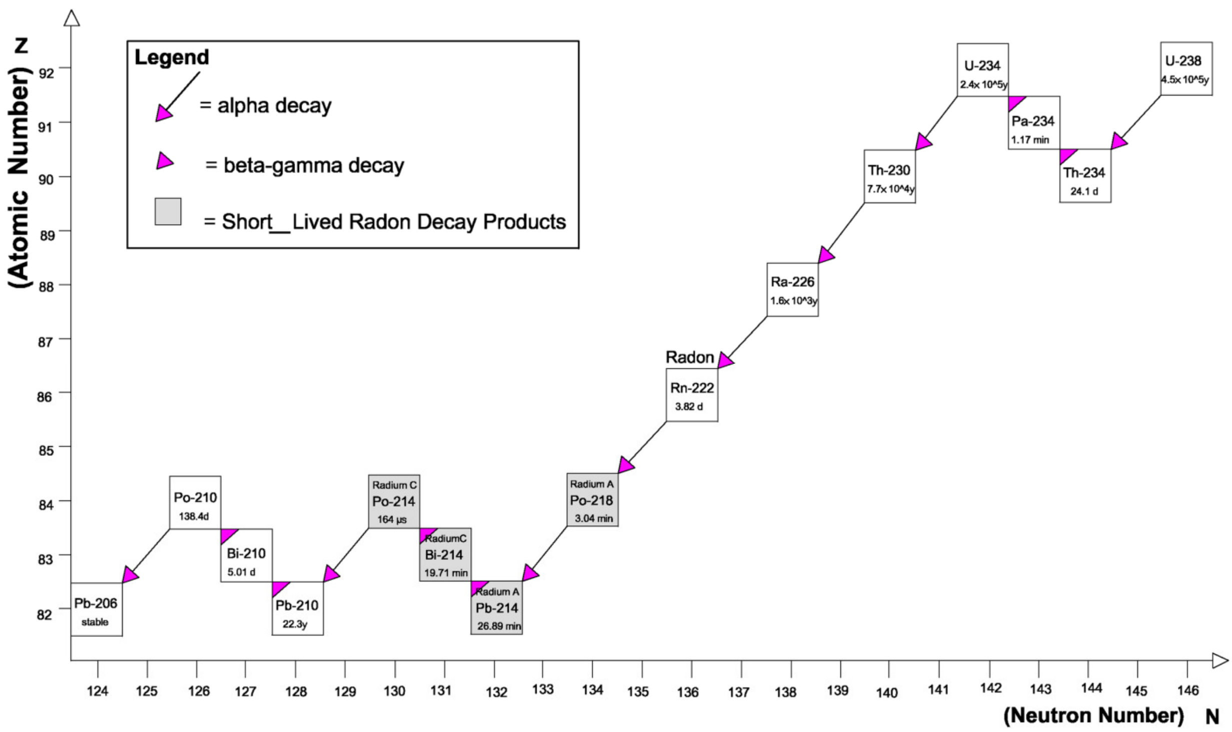


Figure 1: Isotopic decay series of Uranium-238 (from [20]).

2.3 Radon: Rules, Assessment and Planning

In consideration of the effects on the human health previously highlighted, in the last two decades governments and inter-governmental institutions have been issuing several rules in the field of radioprotection of people from the exposure to Radon; these ones can be distinguished, basically, into: (a) actions directed to the reduction of risk in working places and (b) actions directed to obtain the same result in residential places.

In order to harmonize, in all the Member Countries, the radioprotection standards from natural ionizing radiations, especially from Radon, the European Community has passed the European Recommendation 90/143/EURATOM, referring to the following specific reference values for the confined spaces: 400 Bq/m^3, for the existing houses, 200 Bq/m^3, for houses not yet constructed. In addition, the European Community recommended, in the first case, the use of corrective actions if the level would have been exceeded, with an urgency proportional to its effective value and, in the second one, the use of appropriate preventive techniques to guarantee the recommended value.

Later, the European Directive 96/29/EURATOM has regulated, for the working places, the exposure to natural sources of ionizing radiations, asking the Members: (i) to individuate the working activities subject to risk, (ii) to perform adequate controls and (iii) consequently, to impose some limits for these confined spaces.

In May 2000, the Italian Government has acknowledged this Recommendation, incorporating it in the national legislation by means of the D. Lgs. n. 241, as integration of the previous Italian D.L. 17.03.1995, n. 230. At the item III bis, cited D. Lgs n. 241/00 concerns the "*Exposures due to working activities with particular natural radiation sources*", individuating the following activity areas: a) *"Working activities during which workers and, in case, population are exposed to Radon decay products, Thoron decay products, gamma radiations in working places like tunnels, subways, catacombs, caves and, anyway, in every underground working place"*; b) "*Working activities ... in working places ... in well identified areas or with well determined characteristics, where the average annual Radon concentration must not exceed 500 Bq/m^3". Finally,* the article 10-ter, paragraph 2, of the Decree indicates, then, the compulsoriness of the individuation, within 31 august 2005, by the regional Governments, of the geographic areas with different potential of exhaled Radon (A.P.R.E.), the so-called *Radon-prone Areas*.

Unfortunately, as the law did not provide, about this topic, adequate criteria and guidelines for the individuations of the above-mentioned areas, at the moment, most of the Regions have not, yet, complied with the law obligations, within the deadlines established by Decree D. Lgs n. 241/00. In spite of that, however, a lot of work has been made by some Regions to characterize their own territory, referring, in a non-coordinated way, to the procedures adopted by other ones or by European and non-European countries [31-33].

In order to assess the *Radon-prone Areas,* the previously adopted procedures were generally based on the indoor Radon measurements, in analogy to the program performed, on a national scale, by the National Agency for the Environmental Protection (ANPA) [34]. This approach, though valid at a level of epidemiologic research (Radon Vulnerability), does not enable to obtain the complete definition of the "Radon Risk", as it is lacking in the information concerning the factors intervening in the production, transport and entry of Radon into houses and working places (Radon Hazard) [35].

On the basis of the long term researches carried out in the USA and several European Countries, an up-to-date methodology has been developing, based on more integrated analysis, which correlates the obtained indoor values with the geological and environmental factors of the examined territory. In Italy, it is worth to be emphasized the interesting *"a priori"* approach performed by ANPA in the framework of the PERS project (Exhalation Potential of Radon from Soil) and in research partnership with the Servizio Centralizzato Radioisotopi of the Università Cattolica del Sacro Cuore di Roma. The PERS is based on the geostatistical cross-correlation analysis between the basic geological factors which affect, or can affect, the emanation and the exhalation processes of Radon-soil gas and the Indoor Radon gas data from selected sites [35, 36]. This methodology has been already applied and tested both in Veneto Region and in the Autonomous Province of Bolzano [17].

3 The RAD_Campania Program

In order to afford, systematically and organically, the problem of the Radon assessment, prevention and remediation and its use as a natural tracer in the investigation of transport phenomena in natural and anthropogenic environments, some researchers from the University of Salerno have

planned and started the Research Program "RAD_CAMPANIA",
This Program involves in an interdisciplinary way academic and professional skills, like those from Environmental Physics, Geology, Geomorphology, Pedology, Building Engineering and Radiological Epidemiology. It is realized in close collaboration and coordination with the technical staff from the Regional Agency for the Environmental Protection of Campania Region (ARPAC) [37] and the Centre for Applied Research on the Prediction and Prevention of Major Hazards (C.U.G.R.I.).
In general terms, the Program is structured in Projects and Sub-projects, as shown in details in fig. 2, developing interdisciplinary and operative researches concerning the role and utility of the Radon in health, environmental and building studies.
These researches are based on the scientific background acquired at international and national level about Radon and are aimed, in particular, on their implementation in the territorial planning, the water protection and the safeguarding of people from environmental risks [38, 35]. Therefore, the Program deals with the main themes of operative research in environmental studies for the improvement in the actions and activities of the institutionally competent Authorities and Agencies of Campania Region in the soil, water and human health monitoring and protection, according to the national and regional regulations concerning the "Radon Risk".

In the RAD_Campania framework, this paper shows the GIS-based methodology for the individuation and the delimitation of the *Radon-prone Areas*, according to integrated geology-based criteria [39 – 43].

3.1 The "*Radon-prone Areas*" Subproject

This paper describes the basic assumptions and the preliminary results of one of the Projects and Sub-projects shown in fig. 2, in particular, the so-called "*Radon-prone Areas*" Sub-project, focusing on the hierarchical methodological approach and the multi-scale procedure used, which foresees subsequent levels of the investigation and their cartographic representation, with more and more details. That is in agreement with the prescription of the Italian Ministry of Health in the Radon National Plan (2002), in which an "*adaptive*" procedure of evaluation is suggested, asserting that an "*optimal planning of the map foresees its execution in subsequent stages, where the planning of each stage is based on the analysis of the results obtained in the previous stages*". Therefore, the "*Radon-prone Areas*" Sub-Project constitutes the methodological and procedural framework of the more extensive process of planning which responds, from the scientific point of view, to the institutional fulfilments required by the Radon National Plan.
This "Project" requires techniques and procedures adapted at the different scales of territorial analysis, which are interactive and

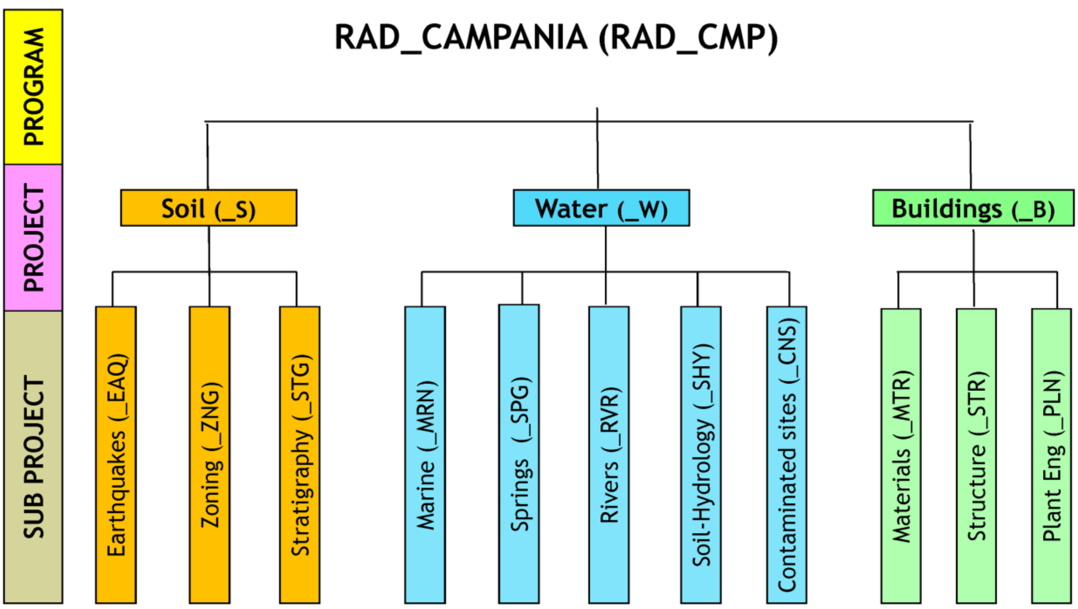


Figure 2: General functional scheme of the "RAD_Campania" Program.

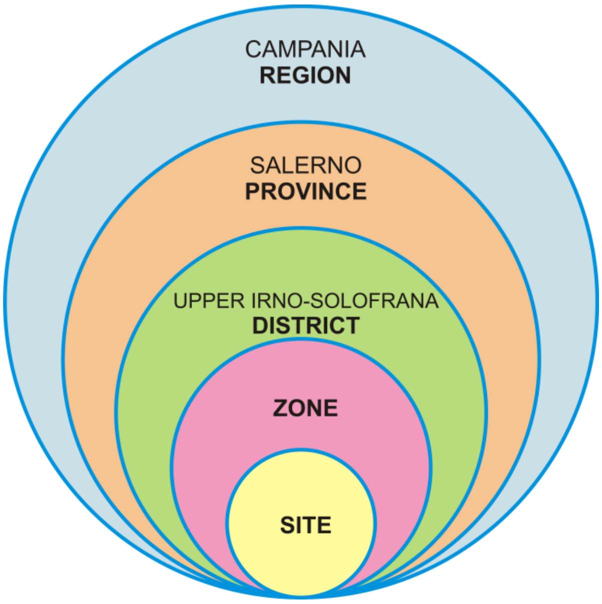


Figure 3: Hierarchical Multi-scale Levels for the Radon-prone Areas in Campania Region

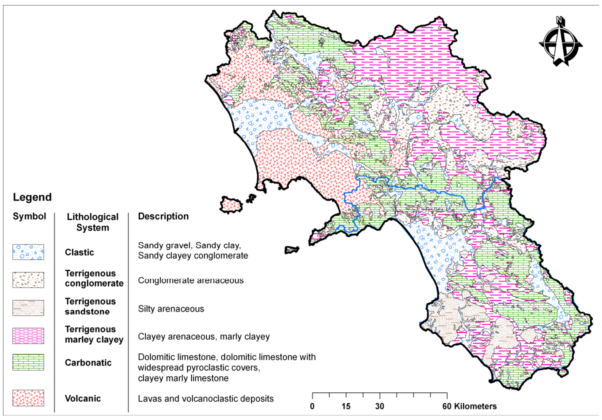


Figure 4: Lithological Systems Map of Campania Region (modified from [45]).

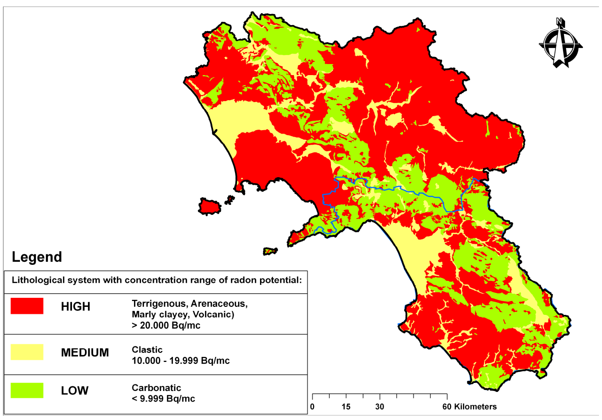


Figure 5: Preliminary Radon-prone Areas Map of Campania Region, Southern Italy, (modified from [42]).

progressively more specific and in depth: from the zoning at a regional scale to the physical-mathematical modelling at a site scale. This approach, called "*Hierarchical and Multi-scale Areas Zoning*", already usefully and widely used in the fields of the environmental planning and landscape ecology [44, 45], is finalized to the individuation, multi-scale classification and assessment of the *Radon-prone Areas,* coherently organized in the following hierarchical levels (Fig. 3).

The Regional Level of analysis provides specific mapping tools , at the scale 1:250.000, suitable for the regional planning, i.e. the Radon Regional Plan, and liable for the implementation in a more general regulation of territorial policy, like the Regional Territorial Plan (PTR).

The Provincial Level of analysis and mapping, at the scale 1:100.000, can be suitable and useful for the sub-regional territorial planning, like the Province Coordination Territorial Plan (PTCP).

At the District level, the analysis, carried at the scale 1:50.000 to 1:25.000, are suitable for Inter-municipal Plans, where high values of the Radon concentration have occurred in the previous analysis level, and it is suitable for the Territorial Planning of aggregates of municipalities (Strategic Urban Plans) and for institutional subjects with tasks aimed at epidemiological investigations, like the Local Sanitary Authorities.

The analysis at the Zone level represents the Radon-soil gas concentration spatial distribution at the scales of 1:5.000-2.000; it is useful for a planning like Municipal Urban Plan.

The Site analysis is useful for Executive Planning, at the scale 1: 2.000, like Executive Plans (PEEP, PIP) and for the Radon-soil gas and Radon Indoor Modelling spatial representations in order to make remediation rules and actions. These last levels are not the subject of the present paper.

Then, in the following sections, the procedure adopted and applied at the different hierarchical levels is synthetically described, whereas the applicative case studies of the procedure adopted at the different hierarchical levels are concisely showed, only from the Regional to the District level.

3.1.1 Analysis at Regional Level

The preliminary assessment of the *Radon-prone Areas* has been made at regional level through two operative steps.

The first step required an updated geological analysis of regional synthesis, with the

individuation and delimitation of the relevant Lithological Systems [45], significant at the used scale of analysis and characterizing the main geological formations outcropping in Campania region (Fig. 4).
The second phase has focused on the search of the bibliographical references reporting correlations between Radon-soil gas and geology (geology-based correlations) and, then, on their application to the geological setting of Campania region. Appropriate *GIS-based* rules have been used for deriving the "*Radon-prone Areas*" Map at the Regional Level (Fig. 5).
The procedure adopted at a Regional Level, built up exclusively on geological and lithological correlations from bibliographic sources, constitutes only an indicative, but not operative tool for planning purposes.

3.1.2 Analysis at Provincial Level: the Salerno Province case study

With the purpose of pursuing the aims of the multi-scale *Radon-prone Areas* Sub-project, with respect to the preliminary elaboration, showed in the previous section, a more articulated and in-depth methodology of analysis has been implemented, in order to give a greater detail setting, considering, besides the lithology, the other main recognized factors contributing to Radon exhalation from soil.
The adopted procedure starts from the assumption, by now acquired in the specific scientific literature, that the geological factors, increasing the probability that an area can show higher levels of *Radon-soil gas* than the average ones [6].
The methodology, already experimented in [39], and, later, developed in [40-43], follows partly the procedures inferred in the PERS Project, adapting them to Campania region and integrating the rules elaborated by J. Wiegand for the compilation of the Radon Guidelines in Germany [46] and for the compilation of the *Radon Status Report* in the State of Illinois, USA [47].
The application of this methodology enabled to set up a preliminary Map of the *Radon-Prone Areas*, still at the Regional Level, but developed for Salerno province only, as a "province case study", considering the geological background and more complete data sets of Radon soil-gas field measurements.
The *Radon-prone Areas* Map is built up by means of the following steps: i) "geology-based" correlations from more specific bibliography; ii) more geological detail than the one at the Regional Level, with the individuation and the mapping of the Lithological Complexes; iii) setting from experimental measurements of Radon soil-gas in different sample sites, located in lithological complexes representative of the provincial landscape; iv) compilation of a map of interpretative synthesis, obtained from the spatial analysis rules, applied in GIS environment, taken into account the specific contributes to the exhalation deriving from various factors (geology, geomorphology, hydrogeology, vegetation etc.) and progressive calibration of the weighted values by the real data acquired from the *in situ* measurements, opportunely recorded and managed in an appropriate Relational Database.
The general procedure for the compilation of the *Radon-prone Areas* Map of Salerno Province, showed in fig. 6, is based on the *Factor Rating Method*, implementing a *GIS_Raster* procedure and adopting a "*cascade*" criteria from progressive analysis steps of the basic factors, grouped in landscape *transfer factors* [44].
Each thematic map (fig. 7), structured in *raster* format (20x20m pixel), corresponds to an unique basic factor (tab. 1-2), with a variable value proportional to its most probable specific contribute in Radon Potential. Among the considered factors listed in tab. 1, only the factor group "geology, permeability and radioactivity" can be directly correlated to the lithological complexes outcropping in the provincial landscape (Tab. 2) and, therefore, they affect the values of concentration of the Potential Radon from the *bedrock*.
The remaining factors, such as tectonics, morphology, karst and vegetation, cannot be associated to the lithology, but connected to hydrological, hydrogeological and hydro-geomorphological effects, each of which is represented on a single thematic map, such that, in every moment of the phase of instrumental and experimental validation, it is possible to discriminate, for each element or factor (Tab. 2), the incidence of the variations in the increment of the Radon-soil gas concentration.
For each combination of values related to the combined subjects, some new values (sum of the ones from the previous two classes) are derived. These values are rearranged to form three new classes for the new thematic map.
For example, from the sum of the combination of the values of the lithology and rock-radio map (respectively 1 for small, 2 for medium and 3 for high), a new range of values (from 2 to 6) is obtained. These new values are then grouped to form a new set of values (from 1 to 3), which are

associated to the three classes (small, medium and high) of the new thematic map.
The basic factors are, therefore, progressively combined to obtain, in sequence, derived thematic maps (Litho-Radio, Geology, Hydrology, Karst-Hydrology, Hydrogeomorphology), and, finally, with successive combinations rules, the synthesis map.
The final Radon-soil Map of Salerno Province (fig. 8) shows a preliminary spatial distribution of the classes in the Radon-soil gas concentration and, then, enables to locate the contiguous areas.
In a preliminary comprehensive analysis of map, the areas with relative higher levels coincide with radioactive, permeable sediments in plain and valley floor affected by active tectonics and karst springs inflow into main river system.

Table 1: modified from [42].

FACTOR 1		
	RADIOACTIVITY	
BEDROCK	LITHO-RADON	
	SOIL PERMEABILITY	
FACTOR		**F**
VEGETATION	Forest	1
	Colture	2
	Meadow or no vegetation	3
MORPHOLOGY	Summit, ridge	1
	Hillslope	2
	Plain	3
TECTONICS	Active fault	3
	Probably active fault	2
	Overthrust or inverse fault	1
KARST FEATURE	Karst spring	3
	River	2
	Karst area	1

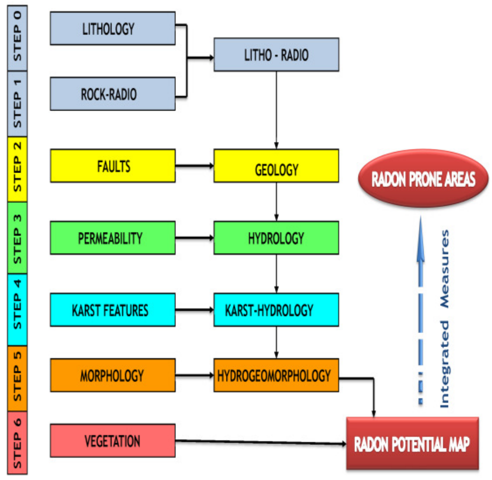


Figure 6: Flow-chart diagram showing the applied methodology for the production of the Radon-prone Areas.

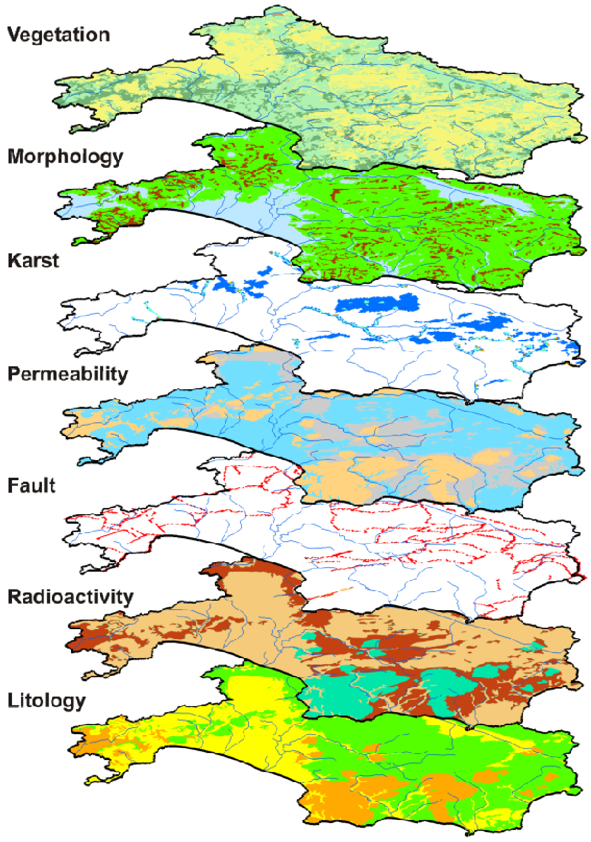
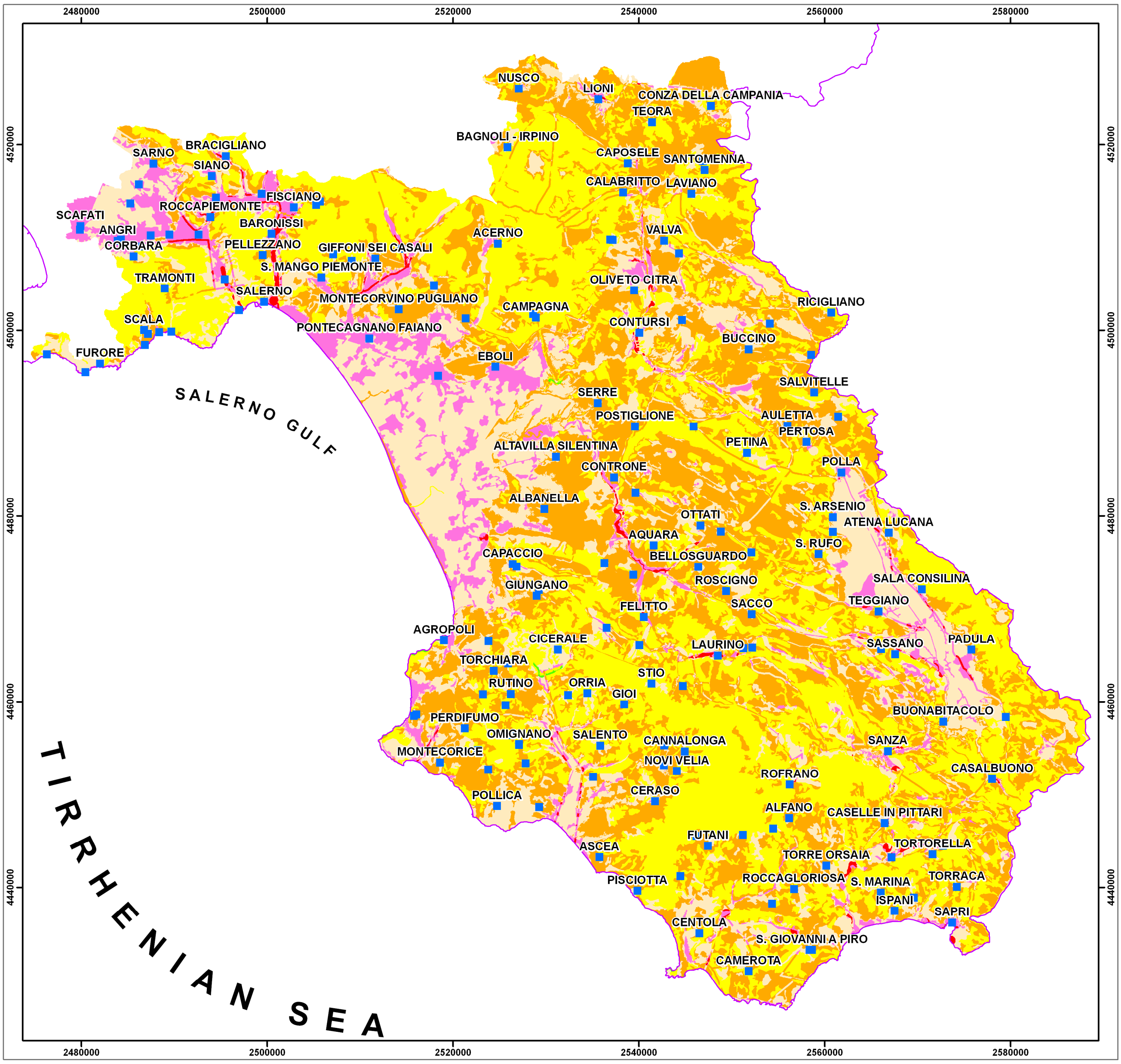


Figure 7: Thematic levels used for the production of the Radon-prone Areas Map of the Salerno Province. (modified from [42]).

Table 2: correlations between the factor group "geology, permeability and radioactivity" with the lithological complexes (modified from [40]).

Cod.	LITHOLOGICAL COMPLEX	SOIL PERMEABILITY			LITHO-RADON			RADIOACTIVITY		
		Permeability Class	Value	Lithological System	Geom. Mean [Rn] (Bq/m^3)	Radon Potential Class	Value	Activity 226Ra (Bq/kg)	Radon Potential Class	Value
1	Conglomeratic Arenaceous	Medium	2	Terrigenous	>30K	High	3	20<A<30	Medium	2
2	Silty Arenaceous	low	1	Terrigenous	>30K	High	3	20<A<30	Medium	2
3	Marly Clayey	low	1	Pelite Terrigenous	<10K	Low	1	>30	High	3
4	Sandy Gravel	high	3	Clastic	10k<c<30k	Medium	2	<20	Low	1
5	Sandy Clayey conglomerate	Medium	2	Clastic	10k<c<30k	Medium	2	<20	Low	1
6	Sandy Clay	low	1	Clastic	<10K	Low	1	>30	High	3
7	Dolomitic Limestone	high	3	Carbonatic	<10K	Low	1	<20	Low	1
8	Dolomitic Limestone with widespread pyroclastic covers	high	3	Carbonatic	10k<c<30k	Medium	2	<20	Low	1
9	Lavas and Vulcanoclastic	Medium	2	Volcanic	>30K	High	3	>30	High	3



Legend

Symbology	Class	Concentration level	Class range	Class area
			Bq/m^3	Km^2
	1	Very Low	< 1000	2
	2	Low	1000 < [Rn-222] < 10.000	1990
	3	Medium Low	10.000 < [Rn-222] < 20.000	1709
	4	Medium	20.000 < [Rn-222] < 30.000	1210
	5	Medium High	30.000 < [Rn-222] < 50.000	349
	6	High	> 50.000	3

Figure 8: Radon-prone *Areas* Map of Salerno Province, scale 1:100.000, (modified from [42]).

3.1.3 Analysis at a District Level: the Upper Irno-Solofrana case study.

In order to perform the "Radon Risk" planning to a more detailed level of analysis, the Radon-prone Areas Map of Salerno Province, enables to proceed to the individuation of homogeneous areas, in which, on the basis of obtained values of in Radon-soil gas concentration and relative control factors, must be subject to specific and priority investigations. This is the case of the Upper Irno-Solofrana District, which, as it is showed in Fig. 9, is included in the classes 5 e 6, with a variable concentration in the range values between 30.000 and 50.000 Bq/m3.

In fact, in order to calibrate the procedure at a Provincial Level, several field measurements of Radon-soil gas have been performed along significant transects (T01 and T02) in the Upper Irno- Solofrana District (fig. 9), where stratigraphical data were available from municipality and private technical archives.

For brevity, here it is shown only the Transect 01, connecting the Roccapiemonte Zone to the Sample Site of Lanzara and, then, the Site of Codola Quarry (fig. 10).

The results of the measurements, in highlighting significant correlations between the Radon-soil gas concentration classes and stratigraphy, enables to indentify and delimit the following Radon-soil gas Homogeneous Litho-Morphologic Zones: i) Hillslope, mantled with variable thickness of pyroclastic cover; ii) Piedmont fan and talus, with pyroclastic matrix-supported colluvial deposits; iii) Plain, filled with pyroclastic deposits, reworked by fluvial processes, interbedded with Campanian Igninbrite Tuff strata (fig. 11).

The results of the elaborations enabled to obtain a coherent and more detailed zoning with respect to the *Radon-prone Areas* obtained at Regional and Provincial levels.

The values of the correlation between Radon soil-gas concentration and corresponding morpho-stratigraphic setting, along the different parts of the Transect 01, have been used to define and extend the concentration class to Homogeneous Litho-Morphologic Zones in the District (fig. 12).

The potentiality of the elaborated cartography, schematically shown in fig. 12, lies in its capability to identify in each Province the Districts with the greatest susceptibility of Radon exhalation from soil and, for each District, the portions of municipal territory which show or could show high Radon concentrations, with the possibility of planning, in a specific way, the measurement campaign in order to define the high risk areas in each municipality.

For example, some preliminary elaborations are reported: they have been processed for the municipal territory of Siano, developing the analysis, at first, for the whole municipal territory (fig. 10) and, then, only, for the portion located in the examined District (figg. 13-14).

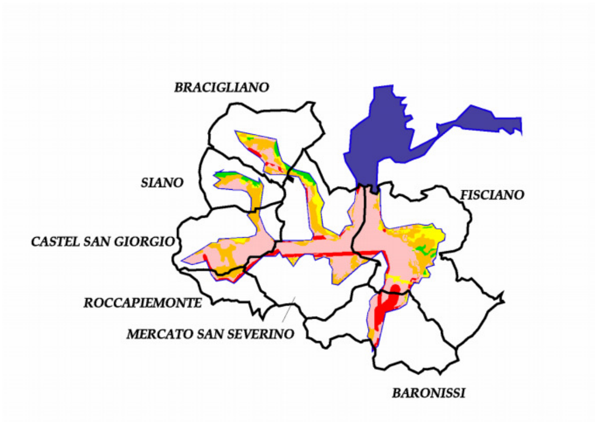


Figure 9: Geographical location of the Upper Irno-Solofrana District and municipality boundary. (modified form [40]).

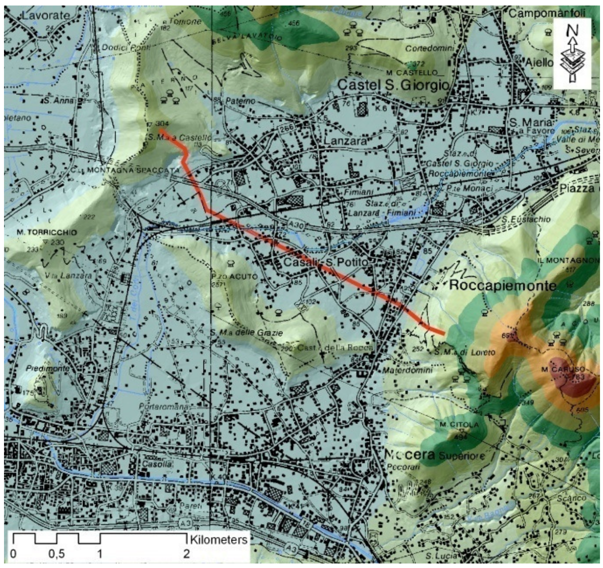


Figure 10: Map location of the Transect 01 and the stratigraphical section trace between Roccapiemonte and Castel San Giorgio towns. (modified form [42]).

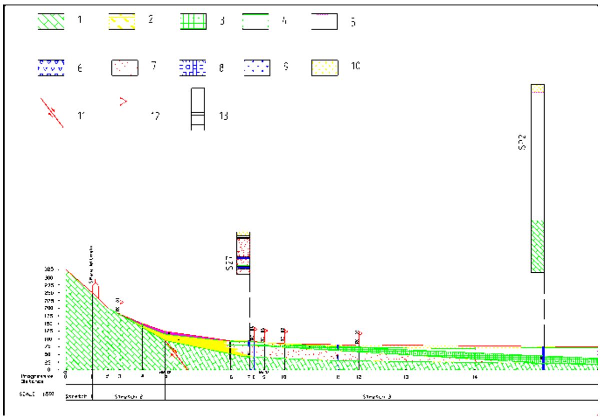


Figure 11: Geo-stratigraphical section along Transect 01 from Roccapiemonte to Castel San Giorgio towns. Symbology: 1. Limestone; 2. Cemented debris; 3. "Grey Tuff"; 4. Clay; 5. Pyroclastic deposits s.l.; 6. Gravel and breccias; 7. Silty sand; 8. Pumix and lapilli; 9. Lapilli; 10.Anthropogenic deposits; 11. Normal fault; 12. Radon-soil gas measurement station; 13: Borehole. (modified form [42]).

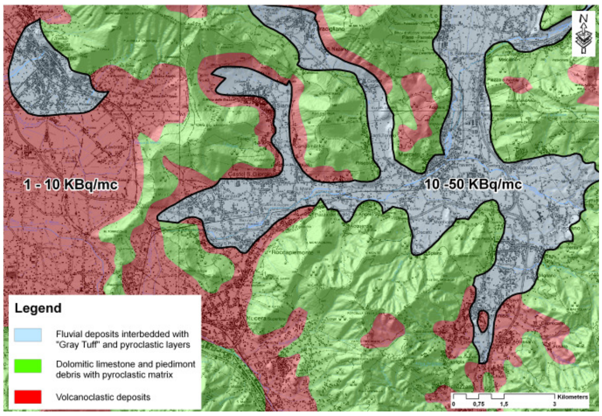


Figure 12: Homogeneous Litho-morphological Zone Delimitation in Radon-soil gas concentration on the basis of the recent geological map at scale 1:10.000 and correlation procedure taking into account the measurement data acquired along Transect 01. (modified form [42]).

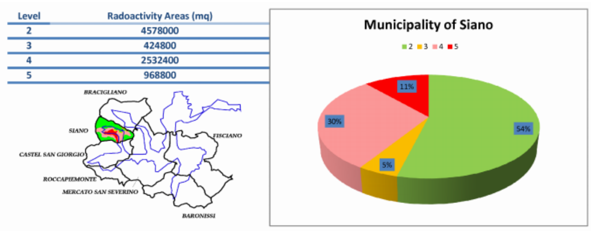


Figure 13: Analysis of distribution in Radon-soil gas classes referred to Siano municipality, as a Reference Territorial Unit. (modified from [40]).

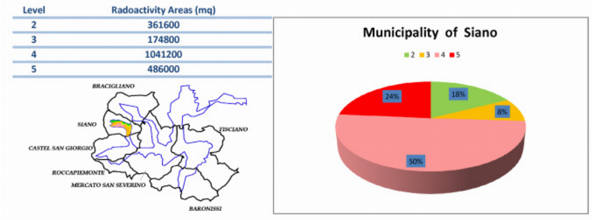


Figure 14: Analysis of distribution in Radon-soil gas classes referred to areas included in the Siano municipality, having the District Upper Irno-Solofrana, as a Reference Territorial Unit. (modified from [42]).

The results of this preliminary application not only highlight the potentials of the adopted methodology and the implemented information system, but they also show the needs of using appropriate reference territorial units, based more on environmental criteria, than on the administrative ones [44].

The "Radon-prone Areas" obtained from the application of the methodology foresees, in succession, the "Radon-soil gas Exhalation Modelling", having as purpose the development of a physical model of Radon-soil exhalation and its progressive setting with the multi-scale zoning by means of calibrated in situ measurements to be performed inside the areas opportunely selected, adopting appropriate sampling protocols. This "Physical Radon Entry and Accumulation Modelling" completes the procedure, providing the basis for a physically-based planning for programming optimized, also in economic terms, epidemiologic investigations in residential environments and in working places.

4 Conclusions

The adopted methodology, therefore, seems to answer the request of the national regulations about the *Radon-prone Areas* and turns out to be suitable for the regional and provincial planning. It also enables to identify the districts and zones where indoor surveys with the highest priority should be concentrated, with remarkable advantages in terms of human and financial resources and, at last, to start the process of progressive cognitive stages investigation in Campania Region, as foreseen by the Radon National Plan (Piano Nazionale Radon, 1998). Indeed, the preliminary results have shown a good correspondence between the *in situ* measured values and the values included in the classes of potential Radon defined in the provisional mapping.

At last, but not with less importance, the exposed methodology reintroduces the role of the Earth Sciences, in general, and of geologists, in particular, in a field relatively neglected by the scientific research and the professional practice. In this sense, one of the targets considered by the RAD_Campania Program is to trigger a technical and institutional process, implementing the subject of "Radon Risk" in the territorial and urban planning, as suggested by M. Moroni [38].

Acknowledgements

The research has been partly financially supported by the Centre for Applied Research on the Prediction and Prevention of Major Hazards (C.U.G.RI.) and University of Salerno FARB research projects. The authors thank the CUGRI former director Prof. Eng. Eugenio Pugliese Carratelli and the Project Manager Eng. Giuseppe Benevento, for the logistic support and the continuous encouragement to explore new fields of research applied to environmental risks.

This work has been made in the framework of the convention between CUGRI and ARPAC (Campania Regional Agency for Environmental Protection): "Rischi derivanti dal superamento dei valori soglia di concentrazione del Radon" (Risks deriving from the overcoming of the Radon concentration threshold values).

The authors, therefore, want to thank Dr. Nicola Adamo and ing. Mariarosaria Della Rocca (ARPAC Executives) for the sensitivity shown towards the territorial problems connected to Radon risk, and for the possibility given to them to implement the methodology, described in this paper, in the institutional context of the agency for the environmental protection.

References:

[1] 13th International Congress of the International Radiation Protection Association, 13-18 May 2012, Glasgow, Scotland.

[2] Darby. S. et al., Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. British Medical Journal, doi:10.1136/bmj.38308.477650.63, 2004.

[3] Neznal, M., Hůlka, J., Radon-Prone Areas – Some Remarks. In: Proceedings of the European Conference on Protection against Radon at Home and at Work, Praha, 1997, 152-155.

[4] Nero A.N., and Nazaroff W.W., Characterising the source of Radon indoors. Radiation Protection Dosimetry, 7, 1984. 23-39.

[5] Gunderson, L.C.S., Reimer, G.M. and Agard, S.S., Correlation between geology, radon in soil gas, and indoor radon in the Reading Prong. In: Geological causes of natural radio-nuclides anomalies (eds. M.A. Marikos and R.H. Hansman), Special publication 4, Missouri, Dept. Natural Resources. Div. Geology & land survey, 1988, pp. 91-102.

[6] Schuman, R.R., and Owen, D.E., Relationships between Geology, equivalent Uranium concentration, and Radon in soil-gas, Fairfax County, Virginia. U.S. Geological Survey Open-File Report 88, 1988, 18-28.

[7] Bolinder, A.S., Owen, D.E., Schumann, R.R., A preliminary evaluation of environmental factors influencing day-to-day and seasonal soil-gas radon concentrations. In: Field studies of radon in rocks, soil, and environment. (Gunderson L. C.S. and Wanty R. B., eds.). USGS. C. K. Smoley Publishers, 1993, 23-31.

[8] Choubey,V. M., Bist, K.S., Saini, N.K. and Ramola, R.C., Relation between soil-gas radon variation and the different lithotectonic units of Garhwal Himalaya, India. Journal of Applied Radiation and Isotopes, 51(5), 1999, 587-592.

[9] Choubey, V.M., Bartarya, S. K. and Ramola, R.C., Radon in Himalayan Springs: A Geohydrological Control. Environmental Geology, 39(6), 2000, 523-530.

[10] Choubey,V.M., Bartarya, S. K., Saini, N. K., and Ramola, R. C., Impact of geohydrology and neotectonic activity on radon concentration in groundwater of intermontane Doon Valley, Outer Himalaya, India. Environmental Geology, 40 (3), 2001, 257-266.

[11] Choubey, V.M., Bartarya, S.K. and Ramola, R.C., Radon variations in an active landslide zone along Pindar River, in Chamoli District, Garhwal Lesser Himalaya, India. Environmental Geology, 47(6), 2005, 745-750.

[12] Miles J.C.H. et aL., Mapping variation in radon potential both between and within geological units. Journal of Radiological Protection, 25, 2005, 257-276.

[13] Piller G., Johner H.-U.,. Classification of Radon Areas in Switzerland. Radiation Protection Dosimetry, 78(1) , 1998, 7-9. Oxford University Press.

[14] Barnet I., Mikšová J., and Fojtikovà I., Indoor-soil gas radon relationship in the Central Bohemian Plutonic Complex, Proceedings of ICGG: p.65-67, Copernicus GmbH, 2003.

[15] Mikšová J. and Barnet I., Radon data processing and outputs for the needs of the State Office for Nuclear Safety (according to the Czech Radon Programme), in Annals of Geophysics, 48(1), February 2005.

[16] Kemski, J., Siehl. A., Stegemann, R., Valdivia-Manchego. M., Mapping the geogenic radon potential in Germany, The Science of the Total Enviroment 272, 2001, 217-230.

[17] Bertolo A. , Verdi L., Validation of a geographical information system for the evaluation of the soil radon exalation potential in South Tyrol and Veneto (Italy). Radiation Protection Dosimetry, 97 (4), 2001, 321-324.

[18] C. Guarnaccia, N.E. Mastorakis, J. Quartieri, Wind Turbine Noise: Theoretical and Experimental Study, International Journal of Mechanics, Issue 3, Vol.5, pp. 129-137 (2011), ISSN: 1998-4448.

[19] C. Guarnaccia, T.L.L. Lenza, N.E. Mastorakis, J. Quartieri, A Comparison between Traffic Noise Experimental Data and Predictive Models Results, International Journal of Mechanics, Issue 4, Vol.5, pp. 379-386 (2011) , ISSN: 1998-4448.

[20] Quartieri J., Troisi A., Guarnaccia C., Lenza TLL, D'Agostino P., D'Ambrosio S., Iannone G., Application of a Predictive Acoustical Software for Modelling Low Speed Train Noise in an Urban Environment, WSEAS Transactions on Systems, Issue 6, Vol.8, pp. 673-682 (2009), ISSN: 1109-2777

[21] Partington, J. R., Discovery of Radon, Nature 179, 1957, 4566.

[22] Majumdar D., Radon: not so noble. Resonance, 2000 , pp. 44-55.

[23] Nero, A.N., Earth, Air, Radon and Home. Physics Today, 42, 1989, 32-39.

[24] Spencer J. E., Radon gas: A geologic hazard. Fieldnotes, 16(4), 1986, Arizona Bureau of Geology and Mineral Technology.

[25] Abu-Samreh M. M., Indoor Radon-222 concentration measurements during the summer season of year 2000 in some houses in the western part of Yatta city. The Arabian Journal for Science and Engineering, 30 (2A), June 2005.

[26] ICRP, Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP 21, 1991, 1-3.

[27] BEIR IV, Health risks of Radon and other internally deposited alpha emitters. National Research Council. Committee on the Biological effects of Ionizing Radiations, National Academy Press, Washington D.C. 1990.

[28] ICRP, Protection Against Radon-222 at Home and at Work. International Commission on Radiological Protection (ICRP), ICRP Publication, 1993. Pergamon Press 23(2), 1993, 1-65, London, England.

[29] BEIR VI, The health effects of exposure to indoor Radon. National Research Council. Committee on the Biological effects of Ionizing Radiations, National Academy Press, Washington D.C. 1998.

[30] Ministero della Salute, Piano Nazionale Radon, Roma, 2002. (in italian).

[31] ARPAV, Indagine regionale per l'individuazione delle aree ad alto potenziale di Radon nel territorio veneto, Regione Veneto, 2000. (in italian).

[32] Verdi, L., Caldognetto, E., Trotti, F., Confronto tra due diversi metodi di mappatura del Radon in Alto Adige. Atti Convegno nazionale "Problemi e tecniche di misura degli agenti fisici in campo ambientale", Provana in Parella (To), 2003.(in italian).

[33] Giannardi C.. Identification in progress of Radon-prone Areas: Toscana and Veneto. Radiation Protection Dosimetry 97, 2001, 349-354.

[34] Bochicchio F. et al., Results of the Representative Italian National Survey on Radon Indoors, Health Physics, 71, 1996.

[35] Moroni M.,. Il Radon. Tecniche di misura e di risanamento con elementi di calcolo, modulistica e legislazione di base. Edizioni de Il Sole 24 Ore S.p.A., 2002. (in italian).

[36] Ponzetti E., Elaborazione statistica dei dati di concentrazione di radon per l'individuazione delle radon-prone areas, Tesi di Specializzazione in Fisica Sanitaria, Scuola di Specializzazione in Fisica Sanitaria, Facoltà di Medicina e Chirurgia, 2004, Università degli Studi di Firenze. (in italian).

[37] ARPAC, Agenti Fisici – Il monitoraggio in Campania 2003 – 2007, Agenzia Regionale per la Protezione Ambientale della Campania (ARPAC) (Regione Campania POR 2000 – 2006). Parte III, 2008, pagg. 169 – 206. ISBN: 978-88-902451-8-3. (in italian).

[38] Moroni M., Il Radon nella Pianificazione Territoriale. INPUT 2001: Informatica e Pianificazione Urbana e Territoriale, Democrazie e Tecnologie, 2001. (in italian).

[39] Cuomo A., Procedura previsionale multiscalare di Area Vasta per la individuazione di aree a diverso potenziale di Radon esalato dal suolo nel settore Alto Irno-Solofrana (Provincia di Salerno*)*. Tesi di Laurea Specialistica in Ingegneria Civile per l'Ambiente ed il Territorio, 2007, Università degli Studi di Salerno, A.A. 2006/2007. (in italian).

[40] Guida D., Guida M., Cuomo A., Iamarino M., Pelosi A., Siervo V., Multi-scale Radon Prone Areas Assessment in Campania Region (Southern Italy). EGU-2008, Vienna.

[41] Guida M., Guida, D., Cuomo, A., Guadagnuolo, D., Siervo, V., Pelosi, A., Serrapica, L., RAD_CAMPANIA: un programma di lavoro su area vasta per la valutazione dell'impatto ambientale del Radon a livello gerarchico multiscalare nella regione Campania. Giornate di studio AIRP – IRPA:"Il rischio da contaminazione radioattiva: i casi radon e uranio impoverito, Paestum, Italy, 29 – 30 Aprile 2008. (in italian).

[42] Guida D., Guida M., Cuomo A., Siervo V., Guadagnuolo, D., Radon-prone Areas Assessment in Campania Region. Applications of a Hierarchical and Multi-scale Approach to the Environmental Planning. Multi-scale Radon Prone Areas Assessment in Campania Region (Southern Italy). Environmental and Technical Geology, vol. XVI, 2008, pp. 38-62, ISSN: 1722-0025.

[43] Cuomo, A., Guadagnuolo, D., Guida, D., Guida, M., Siervo, V. , Assessment of "Radon-prone Areas" on a regional scale by means of a an interdisciplinary adaptive hierarchical multi-scalar approach for the evaluation of the natural radioactivity and the environmental planning in a GIS-based management procedure, Riga Technical University 53rd International Scientific Conference dedicated to the 150th anniversary and The 1st Congress of World Engineers and Riga Polytechnical Institute / RTU Alumni, October 2012, Riga, Latvia.

[44] Guida, D., Guida M., Lanzara R., Vallario A., Proposte metodologiche e procedurali di pianificazione del territorio in aree protette: l'Unità Territoriale di Riferimento. Environmental and Technical Geology – July – September, 1994.

[45] Blasi, C., Guida, D., Siervo, V., Paolanti, M., Michetti, L., Capotorti, C., Smiraglia, D., An integrated, hierarchical, multiscale, gis_based approach to defining and mapping the landscape of Italy. Conference: "EGU General Assembly 2007", EGU2007-A-10822.

[46] Wiegand, J., Radon in Urban Areas. Institut für Geologie, Universität Würzburg, 2005.

[47] Illinois Emergency Management Agency (IEMA), Status Report for Radon in Illinois, edited by Blagojevich R.R. and Burke, W. C., published by the Authority of the State of Illinois (IISG 1095 - 100 – 8/06), USA, 2006.