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S30. Monitoring the Earth for Hazards: Integrating Geology, Geophysics, and Risk Assessment

SELECTION OF HYDROSENSITIVE TO SEISMICITY SITES FOR RADON MONITORING IN THE ABRUZZO AQUIFERS (CENTRAL ITALY) WITHIN THE EUROPEAN ARTEMIS PROJECT

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1. BACKGROUND

Radon is progressively emerging as an effective geogas tracer for geodynamic processes and a potential earthquake precursor (Joint Research Centre of European Commission, 2024; Stoulos et al., 2024, and references therein). Naturally present in groundwater, the radioactive, inert and soluble noble gas 222Rn is an interim product within the 238U to 206Pb decay series. 222Rn formation stems from the alpha decay of 226Ra, which itself is a product of the multi-step decay of 238U. 222Rn, specifically, has a short half-life of around 3.82146 days (Bellotti et al., 2015). The Euratom-funded ArtEmis project (Awareness and resilience through European multi sensor system; https://www.artemisproject.eu/ and https://cordis.europa.eu/project/id/101061712) plans to build aEuropean network of low-cost, multiparametric sensors to monitor radon concentrations in groundwater with high spatial and temporal resolution, on three key areas in Europe. One of these is the Abruzzo region, in central Italy, which has been selected for its significant seismicity and peculiar seismotectonic and hydrogeological features (fig.1). One of the main ArtEmis objectives is to address the long-standing question of whether radon monitoring in groundwater can provide reliable short-term precursors for destructive earthquakes.

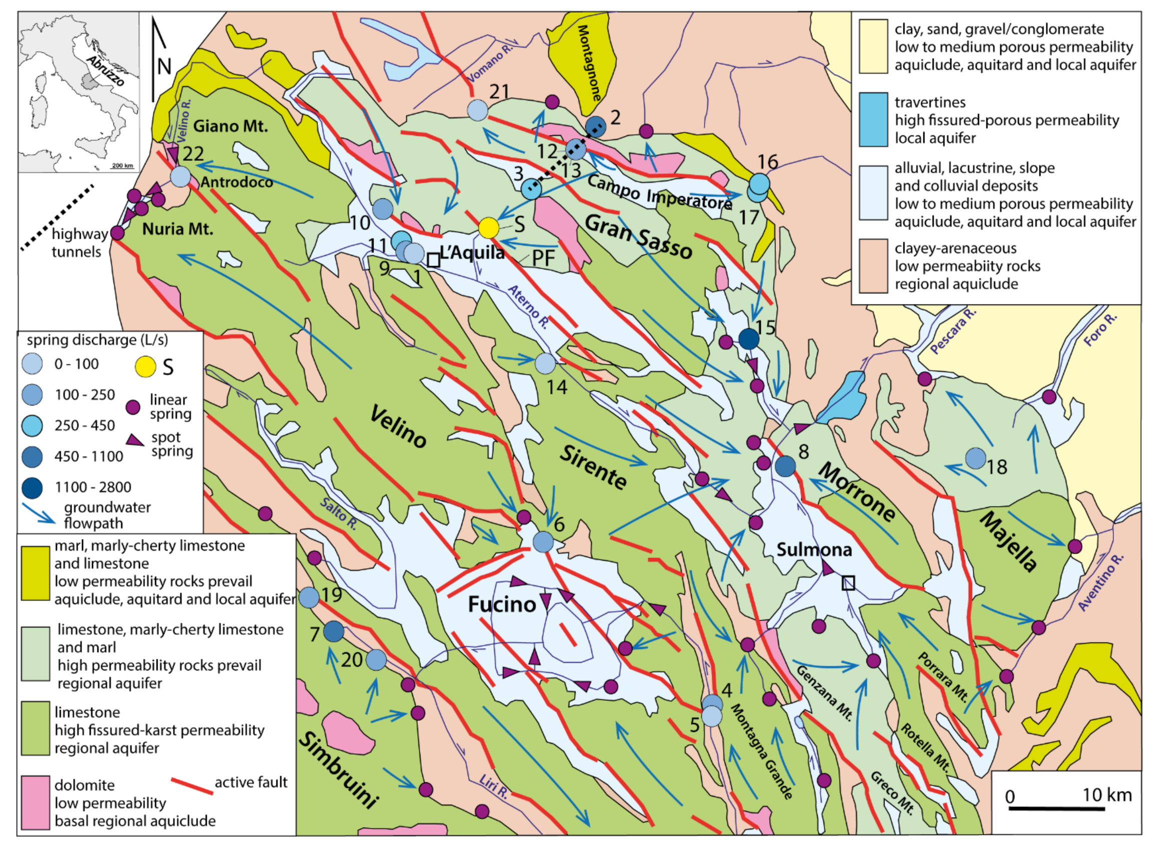

Figure 1: Hydrogeological scheme (modified from Boni et al., 1986 and Celico, 1983) versus active faults sensu Carafa et al. (2022) with the location of the selected sites of table 1, classified based on spring discharge. PF: Paganica seismogenic fault accountable for the April 6, 2009 Mw 6.3 L'Aquila earthquake; S: Tempera-Capovera springs.

2. RESULTS

Particular attention in ArtEmis has been given to the selection of radon monitoring sites in the monitored areas. As radon concentrations in groundwater are believed to be less susceptible to the shallow phenomena than measurements in soil gas, radon monitoring will be carried out only within carefully selected high-discharge springs. Site selection prioritized hydrosensitive to seismicity locations, considering source rock properties, hydrogeological and seismotectonic settings and seismic activity, viewed as main factors affecting radon release.

This work is focused on the selection process of the hydrosensitive to seismicity sites in Abruzzo, where sensors will be installed (fig. 1, tab 1). Source rock properties, hydrogeological conditions, seismotectonic setting, and seismic activity were all considered in site selection due to their influence on radon release into groundwater (figs. 1-5, tab. 1). Sites were chosen within carbonate aquifers, intermontane plains, and spa areas due to the presence of major seismogenic faults, high-discharge springs and the noticeable upwelling of geogas such as CO_2, as potential carrier for radon (figs. 1-5, tab. 1).

These selected springs tap into a significant volume of carbonate aquifer intersected by seismogenic faults, reflecting deep processes, such as the radon upwelling, unaffected by surface ones or significant seasonal variations in the water cycle.

id.	site	aquifer type	discharge (L/s)
1	Pile spring	unconfined perched aquifer, porous media	50
2	NE Gran Sasso tunnels drainage	unconfined regional aquifer, fissured media	900
3	SW Gran Sasso tunnels drainage	unconfined regional aquifer, fissured media	450
4	Pulciara spring	unconfined regional aquifer, fissured media	250
5	Ferriera spring	unconfined regional aquifer, fissured media	50
6	Santissimi Martiri spring	unconfined regional aquifer, fissured media	200
7	Liri spring	unconfined regional aquifer, fissured-karst media	1000
8	Giardino spring	unconfined regional aquifer, fissured media	1100
9	Boschetto spring	unconfined-semiconfined regional aquifer, fissured media	220
10	Acqua Oria well	unconfined regional aquifer, fissured media	200
11	Vetoio spring	unconfined-semiconfined regional aquifer, fissured media	300
12	LNGS underground lab	unconfined regional aquifer, fissured media	200
13	drainage hall	unconfined regional aquifer, fissured media	-
14	Stiffe spring	unconfined regional aquifer, karst-fissured media	100
15	Capo d'acqua spring	unconfined regional aquifer, fissured-karst media	2800
16	Vitella D'Oro spring	unconfined regional aquifer, karst-fissured media	380
17	Mortaio d'Angri spring	unconfined regional aquifer, fissured media	280
18	La Morgia spring	unconfined regional aquifer, karst-fissured media	140
19	Verrecchie spring	unconfined regional aquifer, fissured-karst media	200
20	Rio Sonno spring	unconfined regional aquifer, fissured-karst media	150
21	Chiarino spring	unconfined regional aquifer, fissured media	80
22	Sant'Antonio Bath Antrodoco	unconfined regional aquifer, fissured-karst media	10

Table 1: Hydrogeology of the proposed selected sites in Abruzzo. For the spring group classification see the text. For site location see fig. 1.

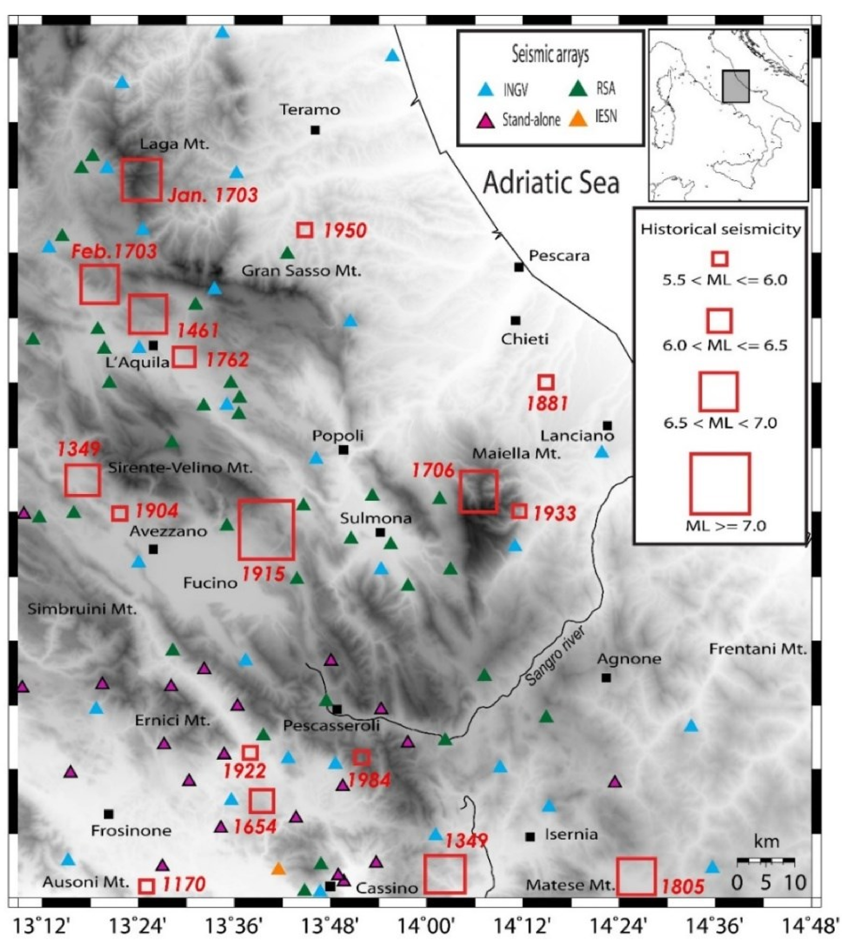

Figure 2: The historical seismicity of Abruzzo. Red squares are proportional to the estimated local magnitude (see box on the right). Large earthquakes occur along the NW-SE striking normal faulting system of central Apennines. Seismic networks: light blue triangles INGV network, dark green triangles Abruzzo regional network, orange triangles IESN network, pink bordered in black triangles temporary station of seismic experiments occurred in the last 20 years (https://emidius.mi.ingv.it/CPTI15-DBMI15).

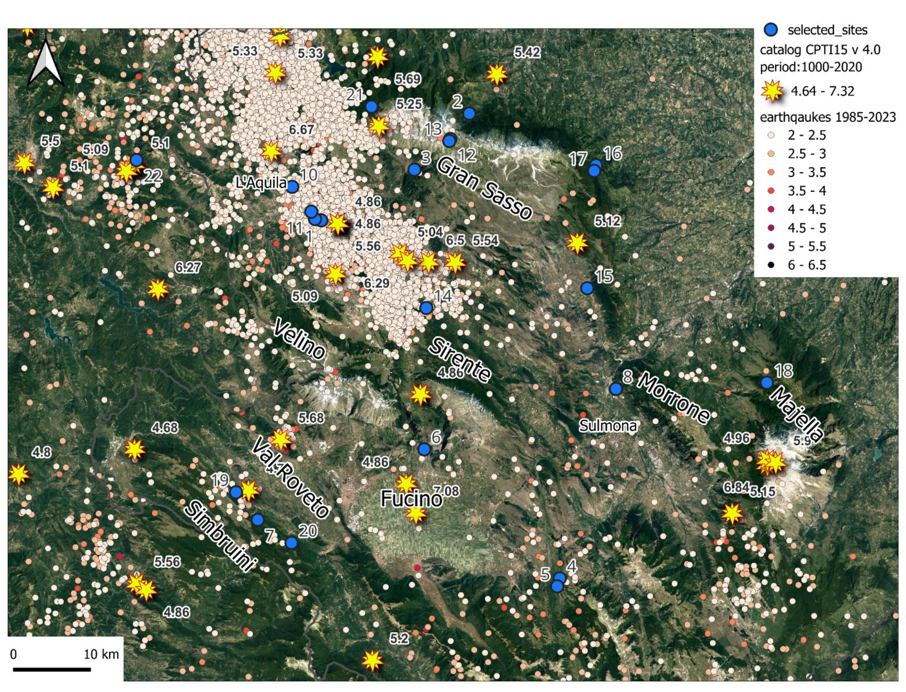

Figure 3: Magnitude of the earthquakes in Abruzzo (events: 14225, period: January 1985-March 2023) and the main earthquakes (CPTI15_v4.0 - catalog of Italian earthquakes from 1000 to 2020) are shown.

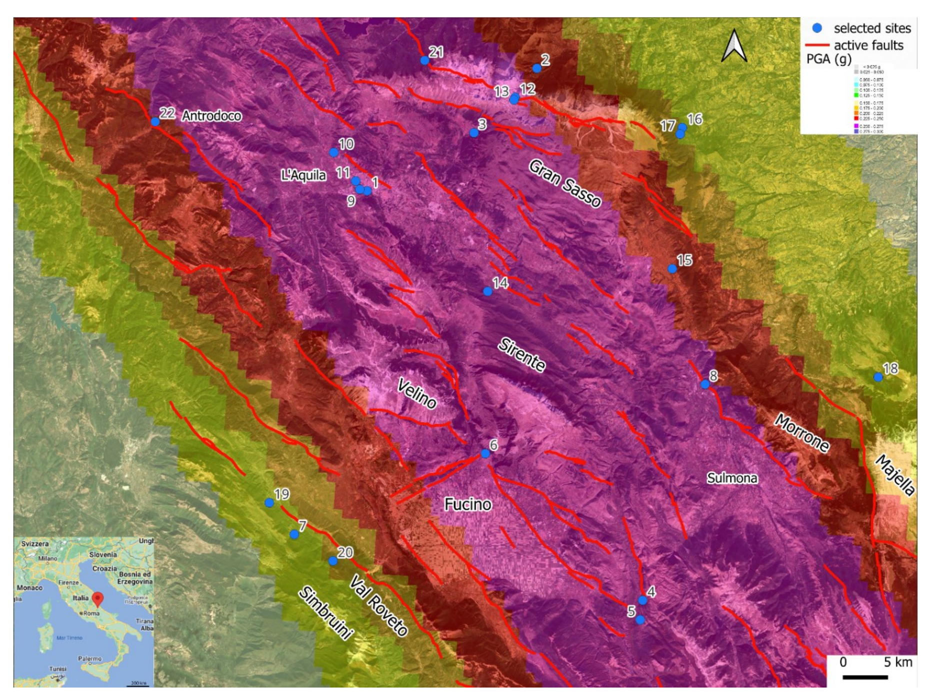

Figure 4: Selected sites for radon monitoring with active normal fault traces from Carafa et al. (2022) and PGA values (Meletti et al., 2006).

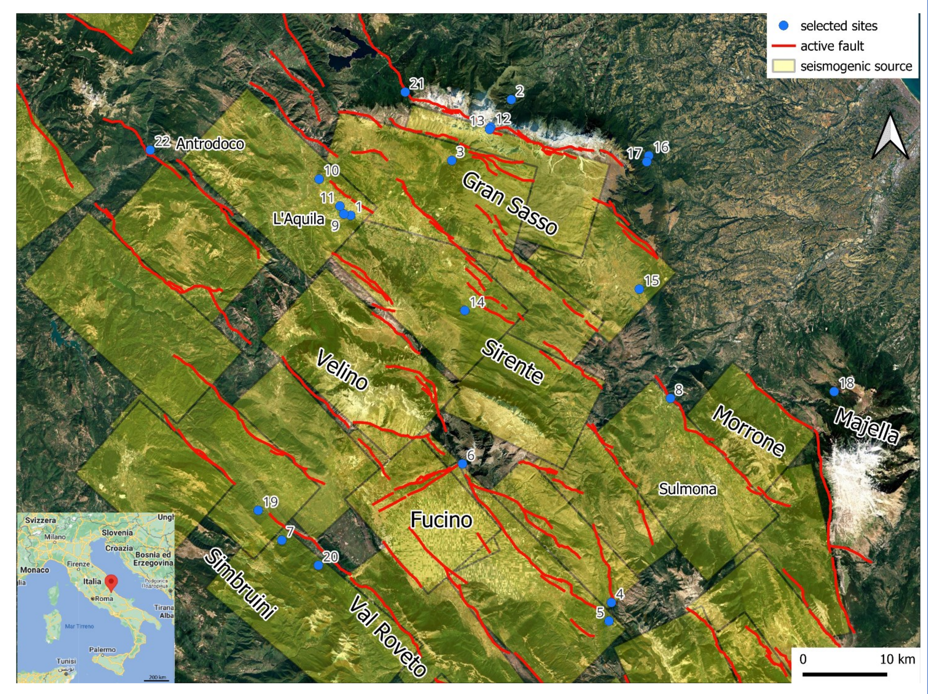

Figure 5: Selected sites for radon monitoring with the seismogenic sources from Carafa et al. (2022).

3. RADON AMOUNT IN GROUNDWATER FROM LITERATURE DATA

In the table 2 and the fig. 6 the radon amount in groundwater (Bq/L) of the main springs of Gran Sasso and Sirente aquifers, considered the representative ones of Abruzzo region, and of Tempera-Capovera springs are illustrated (fig. 1, tab. 1). The Tempera-Capovera springs, within the purpose of the ArtEmis project, are worthy of consideration because they are placed along the Paganica seismogenic fault accountable for the April 6, 2009 Mw 6.3 L'Aquila earthquake (fig. 1).

Groundwaters were acquired before (preseismic period) and after (postseismic period) the occurrence of April 6, 2009 Mw 6.3 L'Aquila earthquake (data from Adinolfi Falcone et al., 2008; 2012; Tallini et al., 2013). These data were used within the ArtEmis project to obtain an order of magnitude of the radon value in groundwater of the most representative carbonate aquifers of Abruzzo and to select the most significant sites within the Abruzzo aquifers where to install the sensors.

About 20 to 50 groundwater sites were sampled. They refer to the principal springs of Gran Sasso and Sirente aquifers, but also groundwater drained by the Gran Sasso highway tunnels. The spot sampling frequency was monthly for the preseismic period (2002-2007) and monthly, weekly or daily for the postseismic period (April 2009-May 2010). Groundwaters were sampled in the field and the samples were taken to the laboratory as quickly as possible, where the analyses were carried out. The radon amount in groundwater were measured in laboratory using an alpha scintillation counter and a Lucas detection cell (the RDA-200 Portable Radon Detector produced by Scintrex, Ontario, Canada). The used technique is reported in Tallini et al. (2013).

During the seismic sequence of 2009 L'Aquila earthquake, the average radon value in groundwater in the preseismic period was almost half that of the postseismic one, both for all the sampled springs at regional scale and for the springs placed along the seismogenic Paganica fault at a local scale (tab. 2).

Furthermore, for the Gran Sasso and Sirente springs, approximately more than 60% of the data shows radon values between 3 and 7 Bq/L and between 0 and 2 Bq/L in the postseismic and preseismic periods, respectively (fig. 6, tab. 2).

Therefore, it is evident that, during the seismic sequence of 2009 L'Aquila earthquake, radon significantly increased in groundwater from the preseismic to the postseismic period at both regional and local scales.

Table 2: Basic groundwater physico-chemical parameters (T, pH, EC) and radon content in groundwater of the selected potential sites from literature data. Data from Adinolfi Falcone et al. (2008; 2012); Barberio et al. (2018); Barbieri et al. (2005); Boni et al. (1986); Conti et al. (2005); Nanni and Rusi (2003); Plastino (2006); Tallini et al. (2013) and from the Abruzzo Water Companies (ACA, CAM) and the Abruzzo Environmental Protection Agency (ARTA). The site codes are in table 1. Preseismic period (pre-09AQE) and postseismic period (post-09AQE) of the April 6, 2009 Mw 6.3 L'Aquila earthquake. (+) average and st. dev. of EC without the outlayer n. 22; (*) average and st. dev. of Rn without the outlayer n. 8.

id.	T (°C)	pH	EC (µS/cm)	Radon (Bq/L)	sampling time
1	11.2	7.46	443	-	T, EC: 1996-1999 pH: 2001-07
2	6.8	8.06	219	0.80	2001-2007 (pre-09AQE)
	6.1	8.00	179	1.54	Sept 2009 (post-09AQE)
3	7.7	8.03	217	0.97	2001-2007 (pre-09AQE)
	6.4	6.78	232	1.44	April 2009 (post-09AQE)
4	6.0	7.91	268	-	May 2023
5	6.0	7.70	290	-	April 2023
6	8.0	7.70	256	-	May 2023
7	7.0	7.65	316	-	April 2023
8	8.5	7.90	311	21.61	T, pH, EC: May 2023 Rn: April-Oct 2017
9	14.2	7.54	415	-	1996-1999
10	10.9	7.65	408	2.47	2001-2007
11	11.1	7.57	396	4.52	2001-2007 (pre-09AQE)
	10.4	7.24	423	5.06	April 2009 (post-09AQE)
12	4.6	8.10	130	2.20	1996-1999
13	6.3	7.93	186	1.21	2001-2007 (pre-09AQE)
	-	8.85	126	2.00	Jan 2015 (post-09AQE)
14	10.3	8.02	444	-	2003-2009
15	11.1	7.55	475	1.65	2001-2007 (pre-09AQE)
	10.6	7.76	465	1.33	April 2009 (post-09AQE)
16	8.0	8.05	277	0.38	2001-2007 (pre-09AQE)
	7.4	8.07	283	3.02	April 2009 (post-09AQE)
17	8.8	7.97	289	1.24	2001-2007 (pre-09AQE)
	9.3	8.10	308	1.56	April 2009 (post-09AQE)
18	11.5	8.09	229	-	May 2023
19	7.0	7.89	289	-	April 2023
20	8.0	7.65	314	-	May 2023
21	6.2	7.94	333	3.63	2001-2007 (pre-09AQE)
	5.7	6.28	278	6.65	April 2009 (post-09AQE)
22	18.0	6.60	1971	-	May 2005
average	8.7	7.73	303 (+)	2.32 (*)	-
st. dev.	2.9	0.50	97 (+)	1.66 (*)	-

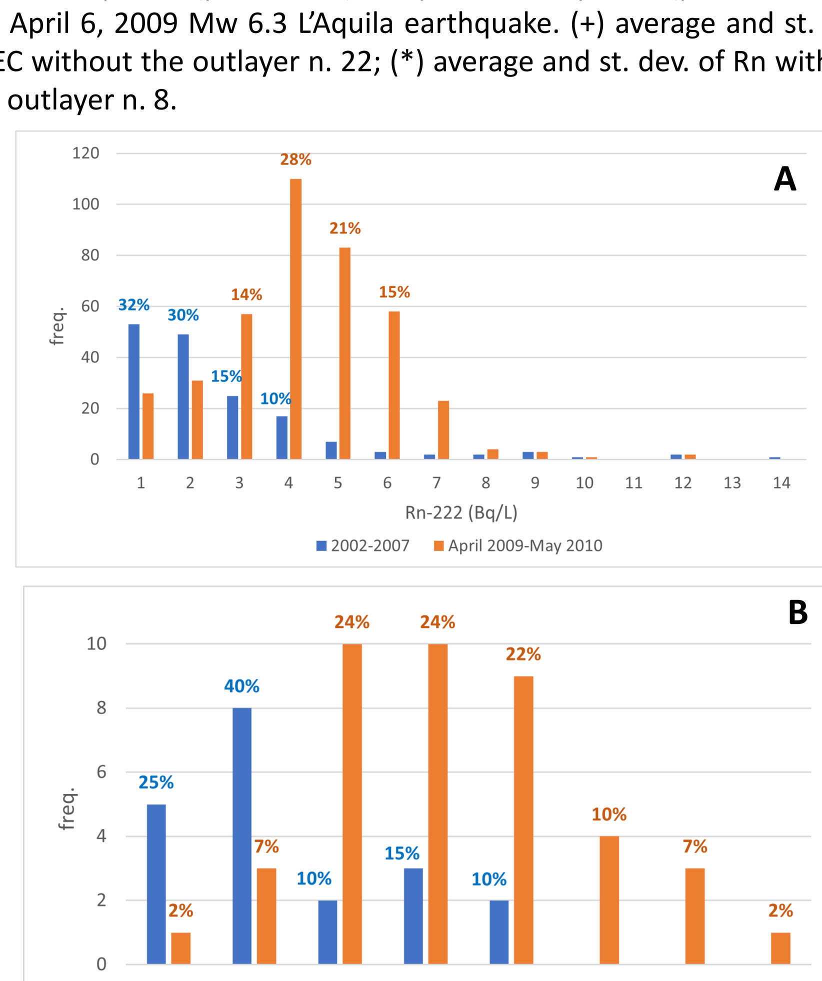

Figure 6: Frequency versus radon range class histogram representing the radon amount in groundwater (Bq/L) of the main springs of Gran Sasso and Sirente aquifers (A) and of Tempera-Capovera springs (B) located along the Paganica fault accountable for the April 6, 2009 Mw 6.3 L'Aquila earthquake. Data were acquired before - preseismic period (blue colour) and after - postseismic period (orange colour) the occurrence of April 6, 2009 Mw 6.3 L'Aquila earthquake (data from Adinolfi Falcone et al., 2008; 2012; Tallini et al., 2013).

4. SENSOR PROTOTYPE INSTALLATON

The ArtEmis sensor is a low-cost, field-deployable gamma detection system designed for real-time monitoring of radon activity in groundwater (Forsman and Gustafsson, 2024). At the core of the device is a CsI(Tl) scintillation crystal coupled with a Silicon Photomultiplier (SiPM) (On Semiconductor), selected for its robustness and sensitivity in the operating temperature range typical of well installations (Scionix). The sensor is enclosed within a watertight plastic casing capable of withstanding hydrostatic pressure at depths up to 3 meters. All components are commercially available and integrated on electronic boards, with data acquisition and transmission managed by a Raspberry Pi processor (Kumar et al., 2025). Communication is established either via LAN/ethernet or mobile networks (3G/4G), allowing for continuous remote data collection.

Following successful laboratory validation, three sensor prototypes within the Gran Sasso carbonate aquifer (n. 2 and 3, in tab. 1) and the Sulmona plain (n. 8, in tab. 1). Real-time data from these sensors is transmitted to a central database at KTH Stockholm, where it is processed using machine learning algorithms to optimize signal analysis. Upgrades made in late 2024 and early 2025 improved power management and communication stability, and a new generation of sensors is currently being deployed.

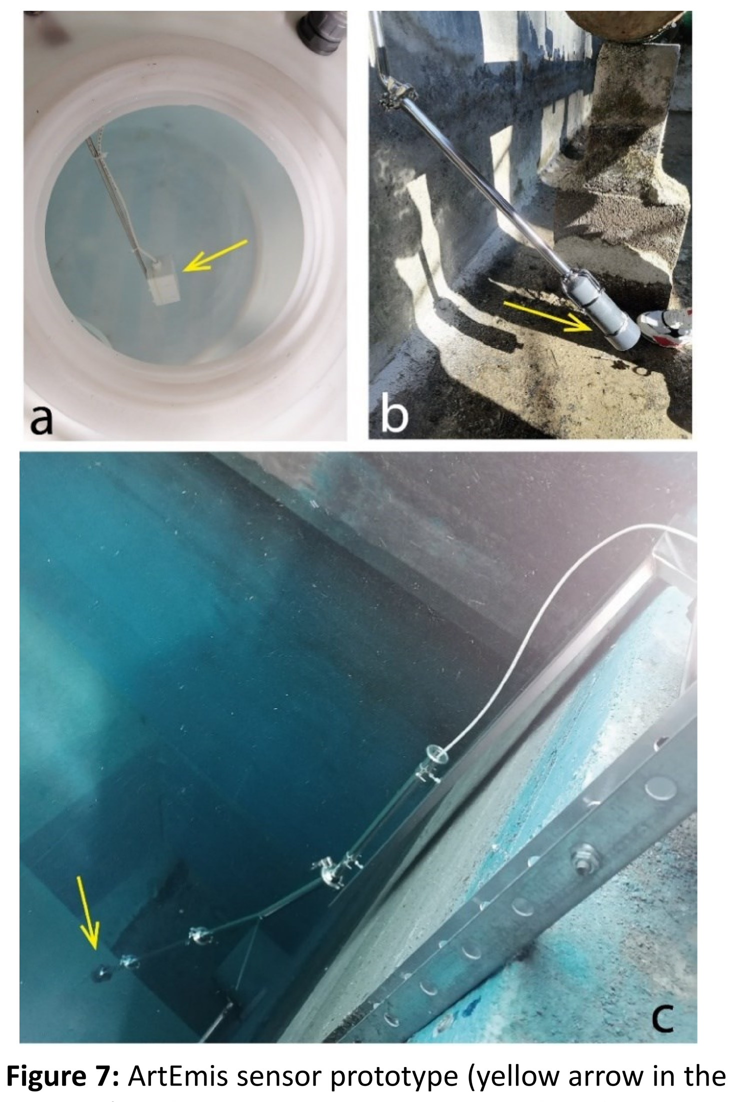

Figure 7: ArtEmis sensor prototype (yellow arrow in the pictures) in the Abruzzo sites; a: sensor placed in a tank (site 2); b: sensor placed in a channel (site 8); c: sensor placed in a hydraulic reservoir (site 3). The site 2, 3 and 8 are located in table 1 and fig. 1.

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