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# Research Article
# Seismic Activity and Geochemical Monitoring of Thermal Waters in Thermopylae

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## Abstract
Results concerning a telemetric multi-sensor measuring station, monitoring six physico-chemical thermal water parameters are reported. The system at its final fully operational stage is capable to continuously measure, transmit and process data. It is located in Greece at Thermopylae hot spring. The study presents a statistical time series analysis for all factors. It further tries to explore if there are some signals that can be considered as precursors to local seismic activity. Some interesting outcomes of the work include emerging periodicities and statistically significant correlations between the involved physico-chemical variables. An important finding is the appearance of six radon anomalies that could be precursor signals to posterior seismic activity. It is the first time that water radon anomalies from seismic activity in Greece have been analyzed.

Key words: Measuring telemetric stations, radon, seismic activity precursors, groundwater hydrology, hydrogeology, engineering geology, modeling/statistics

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

## INTRODUCTION

The implemented telemetric multi-sensor measuring station provides a solution to the research demand form a system capable to monitor continuously physicochemical parameters in ground waters (Popit *et al*., 2005). The measuring station was developed in two phases with the help of two different joint european and national research funding schemes. The present study describes results concerning data from the final implementation and fully working (after various improvements and corrections) system. Reports on earlier developments and outcomes of the station can be found by Avlakiotis *et al*. (2007), Latsos *et al*. (2007), Verros *et al*. (2007) and Zarikas *et al*. (2014a, b).

Seismic activity causes geological deformations extended in a variety of areas and depths and may induce large and detectable modifications in the thermal and physico-chemical characteristics of ground waters. Several works study such variations in the water/soil temperature, chemical composition (concentrations of dissolved gas and ions), in the gas discharge flow-rates (especially $^{222}Rn$), electrical conductivity etc. (Zmazek *et al*., 2002; King *et al*., 1994; Thomas, 1988; Koch and Heinicke, 1994; Dongarra *et al*., 1995; Igarashi *et al*., 1995; Irwin and Barnes, 1980; Koch *et al*., 2003; Wakita, 1978; King, 1980; Nakamura and Wakita, 1984; Wakita *et al*., 1986; Heinicke *et al*., 1995, 2000). Soon, research was oriented towards attempt to achieve some success in the elusive goal of predicting earthquakes. Interesting works about hydro-geochemical precursors of earthquakes include, Wakita (1996), Toutain and Baubron (1999), Thomas (1988), Roeloffs (1988), King *et al*. (2006), Hartmann and Levy (2005), Barsukov *et al*. (1984) and Wakita *et al*. (1988).

An increasing interest of hydro-geologists can be observed the last thirty years for measuring radon emissions. The reason is that radon emissions most probably increase by forthcoming geophysical events as earthquakes. This phenomenon has been studied all over the world. Investigation of anomalies of radon exhalation as a precursory phenomenon correlated to earthquakes is an important field of investigation by Ghosh *et al*. (2009), Cicerone *et al*. (2009), Friedmann (2012) and Woith (2015).

Radon anomalies have been measured in both soil gas and groundwater or springs prior to earthquakes. There are various models proposed in relating precursor time, epicentral distance and magnitude of earthquake. The first who studied radon as a positive tool for prediction of an earthquake was Okabe (1956). He studied possible associations between radon density variation and local seismic activity in Japan (Okabe, 1956). However the last twenty five years with the progress of technology it was possible to develop measuring stations that continuously make observations for time series which last several months to several years. The theoretical geophysical explanation suggests that stresses happening within the earth's surface before and after an earthquake are expected to enhance the radon concentration in soil gas and in ground waters.

Although, many correlations have been found in various countries worldwide, this by no means suggests that it is easy to build a predictive model. There are many complications that are related with the local tectonic characteristics and with the fact that radon concentration levels are considerably influenced by geophysical as well as atmospheric conditions (rainfall and barometric pressure). Hartmann and Levy (2005) concluded that soil radon signals could be confirmed as less reliable, whereas most used hydrochemical signals (changes in groundwater physicochemical parameters) including groundwater radon precursors are correlated more correctly to earthquakes.

A main objective of the study is to present concluding statistical inferences based on data measured by the measuring station at its final fully operational stage. The aim is to utilize the time series of the six factors and present correlations, periodicities, characteristics of the distributions and trends. Furthermore, a main scope of the work is to investigate signal anomalies correlated with nearby earthquake time series. Thus, this study tries to inform the reader about the value of the implemented measuring multi-sensor measuring station and its potential regarding the understanding of the local geophysical and hydrogeological activity including the seismic one.

## MATERIALS AND METHODS

**Telemetric multi-sensor measuring station:** Geological phenomena vary with a plethora of different time frequencies. Certain abrupt geological realignments may occur in a few minutes and the associated modifications on physicochemical follow similar time scales. The measuring station at Thermopylae has an adaptable sampling period. The default setting was 30 min since it is considered to be appropriate for the precise description of the modifications of signal profile in rapid geological phenomena. Some of the key sensors that are integrated in the system are:

**Earth magnetometer:** The measurement of the magnetic field was achieved by using the earth magnetometer model EM2 from AlphaLab. The choice became due to its exceptionally high sensitivity in combination with the relatively low cost.

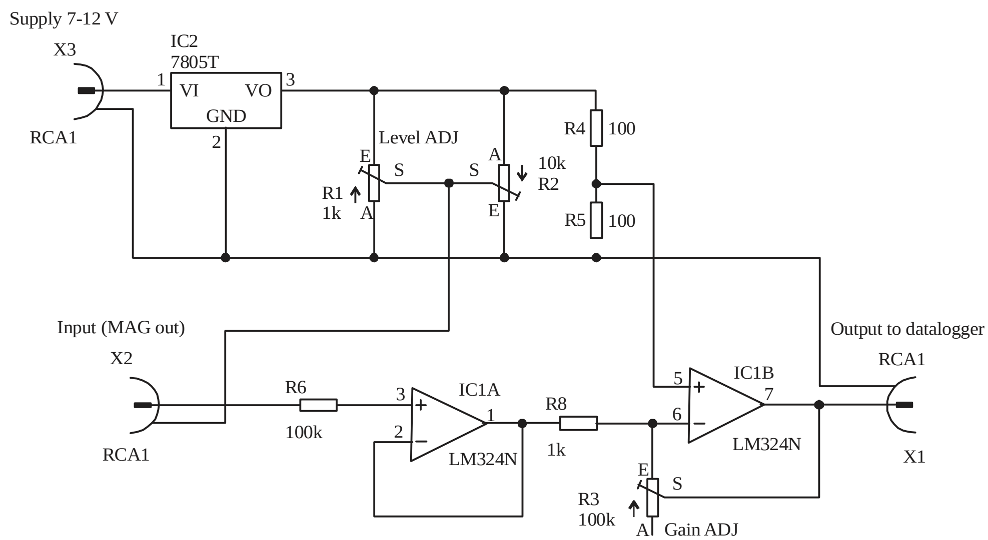


Fig. 1: Circuit schematic diagram

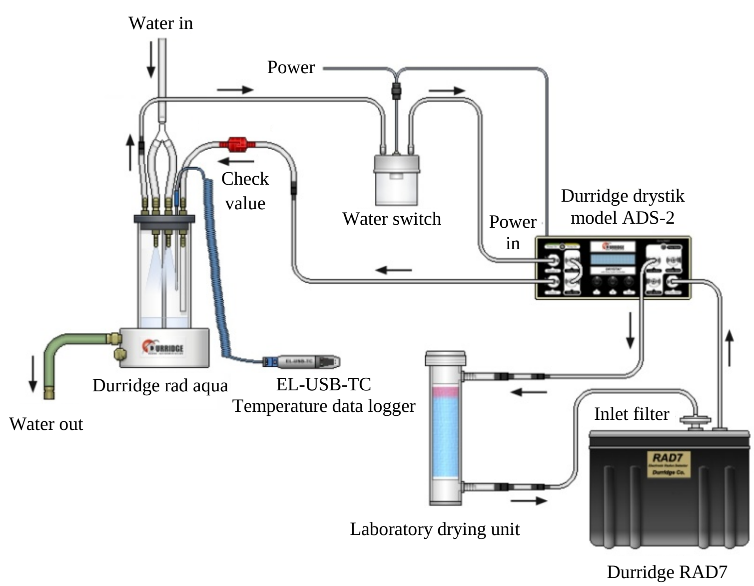


Fig. 2: Durridge RAD7 and RAD AQUA configuration

The characteristics of the instrument are:

- Extend of scale 199.999 μT
- Analysis 0.001 μT (1 nT)
- Precision +/-0.001 μT
- Temperature shift <1.15 nT/°C

The sensor of instrument is based on the Hall effect and can detect both statically and altered magnetic fields. The particular instrument includes neither external interface for PC connection nor simple analogue output, so it's need becomes intervention in the internal circuit of magnetometer and is received analogue signal by a point of the circuit. Afterwards, it was necessary to consider and construct an exterior circuit for the converting and formatting of the signal so as to it is connected with an analogue output of the data logger. Figure 1 shows the circuit and the drawing card (Printed Circuit Board, PCB) that was constructed.

**Radon:** The RAD7 is a highly versatile instrument that can form the basis of a comprehensive radon measurement system (Fig. 2). It may be used in many different modes for different purposes. The RAD7 is a rugged and long lasting piece of equipment. It is a sophisticated, precision electronic device and it is not hermetically sealed. The batteries are lead-acid technology. A useful mode is sniff that lets us make quick, qualitative surveys of radon and thoron levels. It may be used to search for radon entry points. There are some advantages in sniffing for both thoron and radon at the same time, so that is the procedure described here.

After moving to a new location, it will take about 15 min for the count rate to reach equilibrium with the new radon concentration. So, not until after the third 5 min cycle will the reading indicate the new level. However, the thoron daughter, Po-216, has a very short half-life (150 msec), so the response of the RAD7 to thoron is virtually instantaneous. For thoron, the first 5 min cycle is as good as any other. Thoron will only be found very close to radon entry points. That, together with its fast response, makes thoron sniffing an excellent sleuth for radon entry points. To terminate the run any time, it may switch off the RAD7. The data collected, of completed cycles, is stored in the RAD7 memory and available for later display, printing or downloading to a PC.

**pH-ORP:** The equipment was used for the measurement of pH and ORP has the characteristics of pH 7685 from B and C brand. The main features of the instrument are:

- Input from electrode pH (Glass or Antinomy)-electrode ORP
- Temperature input from Pt100 cables
- Alphanumeric lighted up LCD
- Temperature reading
- Double software of filters
- Automatic or manual compensation of temperature
- Isolated proportional exit 0/20 mA or 4/20 mA eligible
- Double points of place with the eligible action: open-closed
  - PFM analogue Pulse Frequency Modulation
  - PWM analogue Pulse Width Modulation with delay and the minimal/maximum programmable operations
- Continuous or flashing alarm
- Minimum/maximum and alarm relay for synchronization total point
- Parameters saving in EEPROM
- Overloading automatic protection and restart
- Removable external poles (1/4" DIN) 96×96

**Statistical methods:** Data used in the present statistical analysis refer to the time duration from 1/10/2014-13/10/2015. The measured factors are: Radon ($^{222}Rn$) concentration in water in Bq $m^{-3}$, geomagnetic field strength (nT), water temperature in Celsius degrees, redox potential (ORP) in milli-volts, pH as a measure of acidity and electrical conductivity in milli-siemens. The software package SPSS v21 software was used to perform various statistical techniques concerning time series (Box and Jenkins, 1976; Bloomfield, 1976; Fuller, 1976; Bartlett, 1946; Cryer, 1986; Quenouville, 1949; Makridakis *et al*., 1983; Gardner, 1985).

**Statistics:** First descriptive statistical analysis was accomplished. Since the study of the type of distributions for each measured variable has geophysical importance various statistical quantities and tests have been used. Skewness and kurtosis were evaluated as measures of deviations from normality. In addition P-P plots and Q-Q plots were drawn for each variable (Kotz and Johnson, 1988). A P-P (Q-Q) plot is constructed by plotting a variable's cumulative proportions (the quantiles of a variable's distribution) against the cumulative proportions (the quantiles) of any of a number of test distributions. These are called probability plots and with the help of them it is possible to explore if the distribution of a factor matches a given distribution. A Q-Q (Quantile-Quantile) plot differs from the probability plot in that it shows observed and expected values instead of percentages on the X and Y axes. If all the scatter points are close to the reference line, it can by said that the dataset follows the given distribution. In the case of a matching of the test distribution the points are gathering around a straight line.

In surveys like the one presented here it is almost always interesting to investigate the existence of correlations. Here correlations were explored using several methods. First, the Pearson correlation coefficient between two scale variables was used for the variables that are close to normality. In addition the non parametric methods of the Spearman's rho and Kendall's tau-b statistics were used for all variables. These evaluate the rank-order association between two scale variables. Non parametric tests are valid for data that deviate from normality. It is also necessary as a final step of the correlation analysis to use the partial correlation method in order to check if a correlation can be removed/weakened due to the presence of a control variable.

As part of the time series analysis a seasonal decomposition procedure was followed. Each variable was decomposed into a seasonal component (periodic component), a total trend and an error component. The algorithm used to implement version of the census method I, also known as the ratio-to-moving-average method. The algorithmic adjustment can remove the seasonal effect from the observed values in order to explore other characteristics which may be hidden by the seasonal component. In particular the autocorrelation function and the partial autocorrelation function are evaluated and plotted for definitive conclusion.

In general autocorrelation is defined as the linear dependence of a variable with itself at two points in time. In the case of stationary processes, autocorrelation between any two observations only depends on the time lag h, between them. It is given by the expression as follows:

$$\rho_h = \text{Corr}\ (y_t, y_{t-h}) = \gamma_h/\gamma_0 \tag{1}$$

where, the covariance is included in the form of $\gamma_h$ = Cov ($y_t$, $y_{t-h}$) Now, partial autocorrelation is the autocorrelation between $y_t$ and $y_{t-h}$ but after eliminating possible linear dependences on $y_1$, $y_2$,...,$y_{t-h+1}$. The autocorrelation function evaluates how a series is correlated with itself at different lags. If data is strongly seasonal, peaks will coincide with the seasonality period. Thus it is possible to infer the seasonality. It is also a tool to confirm any trend, for a positive trend autocorrelation function reduces very slowly. The partial autocorrelation function can be seen as a regression of the series against its past lags. The terms can be viewed as in the standard linear regression, that is the contribution of a change in that particular lag while holding others constant. If an important peak at a lag associated with a number X appears, this indicates the presence of a X times the lag period seasonal component in the time series.

Furthermore, spectral plots for all six variables were drawn; with the help of these plots it is easy to spot the periodic components of different frequencies. The plots are based on fast fourier analysis and show a number of consecutive peaks that are distinguished from the background noise. Both smoothed and unsmoothed spectral plots were constructed in order to better interpret the peaks. The algorithm for smoothing that was used is the Tukey-Hamming; the implemented code is capable to reduce the background noise from the periodogram and thus helps uncovering the underlying structure.

**Signal anomaly:** A radon anomaly is an excess or reduction of two or more standard deviations from the mean value of the studied time series. If it is associated with an earthquake it disappears after the event due to pressure or tension relaxations, healing of the relevant area and exhaustion of gas production.

During the last 45 years almost 90 studies appeared in the literature, which describe 150 concrete and non trivial in duration timeseries (Ghosh *et al*., 2009; Woith, 2015). The number of these experimental studies is not big and it could be considered even smaller taking into account that only 51 cases refer to radon (dissolved) in groundwater. The discovery of earthquakes precursors from ground water signals is much more reliable since it is much more probable the anomaly to have been caused by a geological deformation from the posterior seismic activity. Anomalies reported from soil gas case studies are more problematic. It has been proven that are subject to non seismic origin sudden increases or decreases of radon.

Almost all papers that report anomalies work with the same approach for identifying what is a signal anomaly. However, they follow vague selection criteria or at the best specific arbitrary rules. The rules specify how to choose signals and if these selected signals can be regarded as a precursor; for example: One radon anomaly is related to one earthquake.

The anomaly excess definition is more or less common in all works (two standard deviations above the mean value). The choice of the associated to the anomaly earthquakes is more arbitrary. There are mainly two kinds of rules as selection criteria. The survey is focus in one preselected seismogenic area. Measuring instruments are located and are designed to observe a certain seismic rift system or a seismically active zone. The investigation of radon anomalies refers always to signals prior to earthquakes happening in this area. A second option is to analyze all measured signals and select as precursors signals with an anomalous radon concentration peak happening some days or weeks prior to an earthquake. The earthquake is selected from a list of earthquakes that are characterized with a large strain impact (small E/D) according to an empirical formula provided by Dobrovolsky *et al*. (1979). This second method is followed in the present study.

The idea behind this dobrovolski criterion is that when the distance (E in km) between the thermal water sample collection point and the earthquake epicentre is shorter than the so called "strain radius" (D), then it is more probable to observe considerable increased radon concentration. The strain radius determines an area in which the geological effects of an earthquake with Magnitude (M) are significant and is given by the empirical equation:

$$D = 10^{0.43M} \tag{2}$$

In summary the method consists of three steps; (1) Find anomalous signals that are characterized with a minimum peak two standard deviations above the mean value, (2) Construct a list of nearby earthquakes with small E/D and (3) Select the set of anomalous signals with small E/D that are happening×days before an earthquake belonging to the previous mentioned list. In this study, the value of X is set to 10 days.

It is obvious that the use of common statistical techniques that offer expressive tools to correlate one variable and its time series with another variable and its time evolution has no meaning in the context of spotting seismic precursors. The reason is that earthquakes are rare and are happening in different locations and with different characteristics and their analysis needs to accomplish a geological theoretical model like this, that is proposed through the impact strain radius of dobrovolski.

## RESULTS AND DISCUSSION

Descriptive statistical analysis and the P-P and Q-Q plots reveal that the variables magnetic field, water temperature and pH are close to a normal distribution. On the other hand, radon concentration, conductivity and redox potential ORP excibit strong deviations from normality. The descriptive statistics of the six factors in the form of Mean value±Standard deviation are: T= 40.18±0.65 (Celcius), OPR (absolute) = 450.38±85.32 (mV), pH = 6.18±0.18, Conductivity = 24.41±1.16 (mS), Magnetic Strength = 51868.05± 6542.92 (nT) and Radon = 726.38 ±145.3 (Bq $m^{-3}$).

At this point the reader would be advised to see the lengthy presentation of a similar data analysis from an earlier pilot functioning of the measuring station (Zarikas *et al*., 2014a). Although both data and dataset are different, some key features of the analysis are the same. The study by Zarikas *et al*. (2014a) presents the reasoning of the interpretation of intermediate figures that is needed to be drawn in order to reach statistical conclusion. Here, it was chosen to present only the statistical inferences and do not include again explanatory intermediate figures which are too many.

The search for correlations discloses some statistically significant correlations between variables. Both parametric and non parametric methods for possible associations found in agreement mild associations between the variable pairs: temperature with radon concentration, temperature with ORP, ORP with pH and temperature with pH. In addition we have explored if there is a control variable that may eliminate the previous correlations. All the possible combinations of the six variables have been checked with the conclusion that all correlations remain. However, the correlation OPR with pH, using temperature as control variable, becomes milder although still significant.

The fast fourier analysis generated several spectral plots for each of the six variables. The study of the smoothed and unsmoothed periodograms indicates a 24 h periodicity for temperature and pH variables and a 12 h periodicity for radon, temperature and pH. Although, our time series are just above a year, it was possible to spot six month half-period modes in the spectral modes of temperature, conductivity and pH. The OPR and magnetic field strength do not exhibit any significant periodicity. Radon concentrations, temperature, pH and conductivity follow also an eight days period (radon does not show this periodicity for all months). Twelve hours periodicity is most probably caused from sea tides; thermal waters at Thermopylae location are mixed with salty water from the nearby coast. Twenty four hours periodicity is due to the day night cycle while the almost 7.5 days periodicity found, may be associated with the spring and neap sea tides entering the underground tank of water.

The statistical inferences presented here coincide with previous results although there are some differences. In particular, the present study compared to the work by Zarikas *et al*. (2014a) exhibits minor differences concerning the mean values of variables. Mean values of temperature and pH are somewhat smaller while the absolute OPR and conductivity mean values are moderately larger. Note also that the present study reports results from the final stage of the developed measuring station which also includes two extra sensors that measure radon and magnetic field. Furthermore, the present study confirms the absence of periodicities for OPR and the existence of the periodicities for temperature and pH found by Zarikas *et al*. (2014a). However, since the final version of the measuring station provides measurements with less noise, it is possible to spot more clearly the fourier modes. In addition, some missing values have been replaced with the help of the statistical technique for missing data imputation (Zarikas *et al*., 2014b). This is the reason why in the present study new periodicities found for conductivity and temperature. Furthermore, emerging correlations agree with those reported by Zarikas *et al*. (2014a) with the addition of the radon temperature correlation.

Perhaps the most interesting outcome of the present study is the results from the comparison of the time evolution of the six measured variables with the local seismic activity. Indicative time series are shown in Fig. 3-7, while Fig. 8 shows the time series of the quantity E/D for all earthquakes with E<65 km. There are 17 earthquakes with stress ratio E/D<1

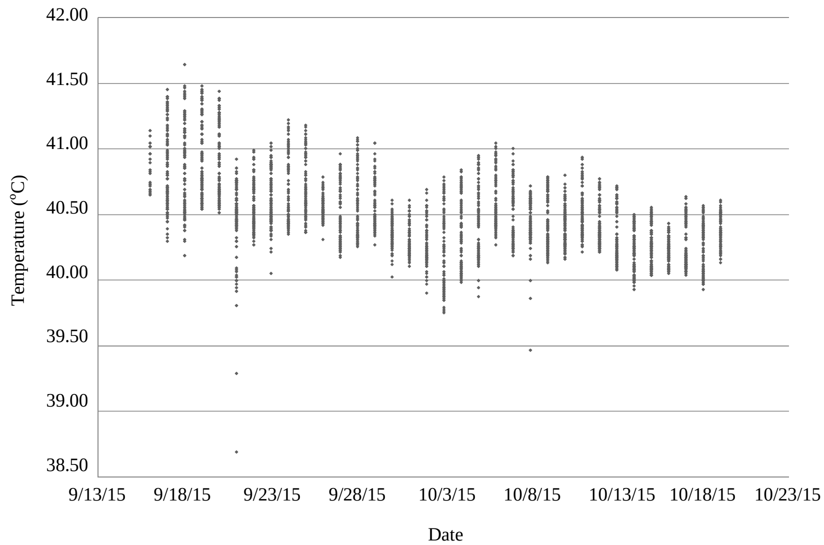


Fig. 3: Typical monthly water temperature time series

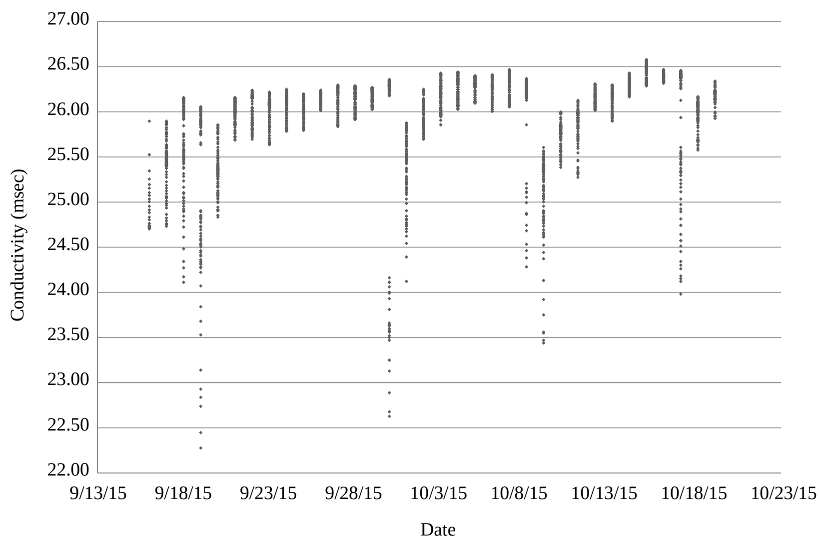


Fig. 4: Typical monthly conductivity time series

and 31 earthquakes with E/D<1.5, in the time interval from 1-9-2014 till 14-10-2015. The study includes 1469 earthquakes that occurred in the examined time interval and within 65 km from the measuring station. However, note that some of the 1469 events are associated to the same main earthquake. The sample is considered satisfactory since several critical geological events occurred capable to generate geological deformations resulting to an excess on the radon concentrations.

In order to spot easier and safer anomalies it was mentioned that we work with the arbitrary rule that there must be an excess of two standard deviations 1-10 days prior to an earthquake with small E/D. This is a very conservative rule that enhances the probability a reported factor excitation to be the result of an earthquake. Of all the six measured variables, only radon concentration exhibits anomalies following the above rule. There was also one case for the variable OPR with excess equal to 1.5 σ and two cases (1.7 and 1.8 σ) for conductivity. Table 1 shows some distinguished cases for the radon concentration. In this table six clear anomalies can be observed. One of them was for a quite strong earthquake that happened very close to the measuring station. There is also a radon anomaly that was attributed to an earthquake with E/D = 1.2.

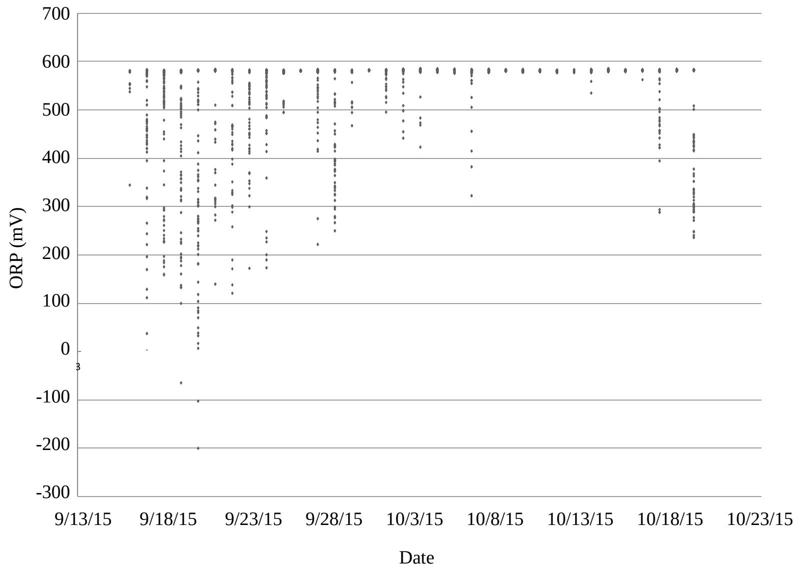


Fig. 5: Typical monthly OPR time series

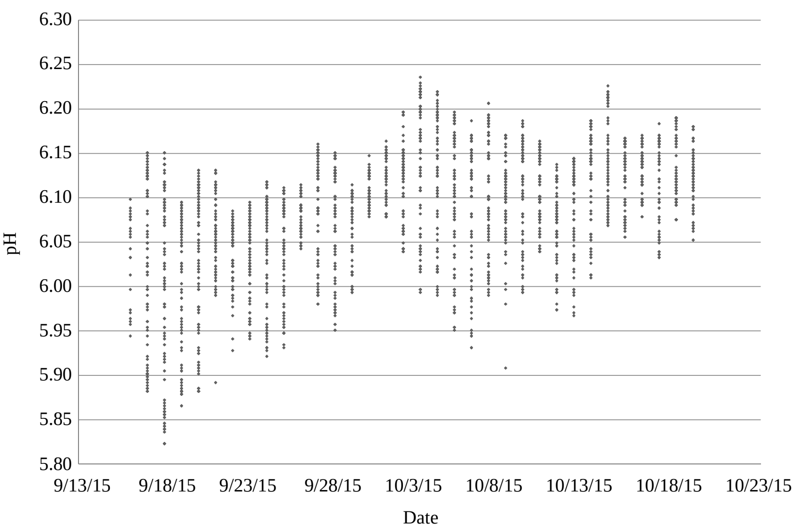


Fig. 6: Typical monthly pH time series

The overall conclusion of the search for precursor signals to earthquakes coincides with previous works and confirms Dobrovolski's criterion as a useful and indicative one. Although several radon anomalies were emerged, there are some cases with events associated with small E/D ratio that it was not possible to be related with an anomaly. This is not a surprise since each earthquake generates different geological deformations.

Last decades considerable effort has been devoted worldwide for the discovery of radon anomalies. Two indicative works will be further annotated; they were selected trying to find publications that describe similar cases like the one of the present study i.e., continuous monitoring of thermal springs. In study of Popit *et al*. (2005), authors report radon anomalies in thermal waters in Slovenia. The analyzed time series refer to one year measurements from two nearby locations. The final conclusion in Popit *et al*. (2005) is in favor of the theory of the stress-strain field defined by Dobrovolsky *et al*. (1979). This study confirms such a claim. One difference with the present study is that our thermal waters have much less mean radon concentration. On the other hand Thermopylae location is associated with much more seismic activity. Another work that studies radon concentration anomalies in thermal waters (Das *et al*., 2006)

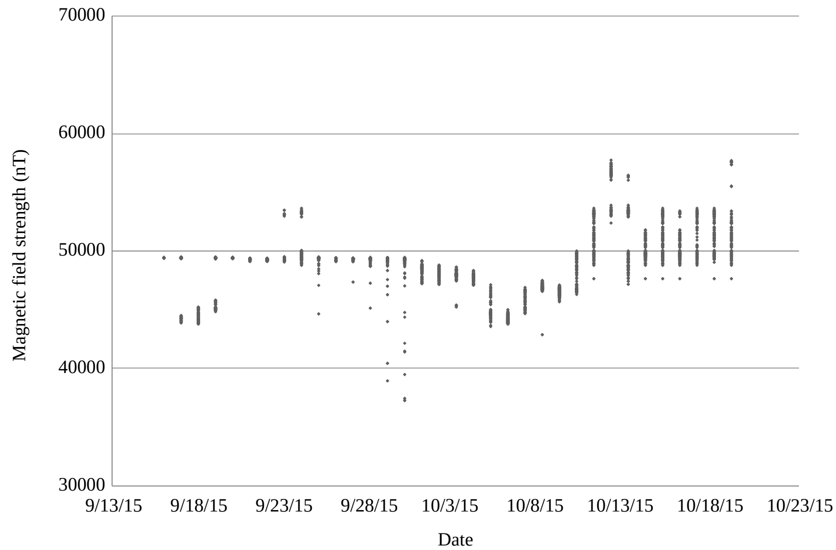


Fig. 7: Typical monthly magnetic field time series

Table 1: List of all earthquakes with small E/D. The last column shows how many days before the earthquake, a radon anomaly starts to be observed

| Date | Latitude | Longitude | Depth | Magnitude | E (km) | D | E/D | Days of radon anomaly |
|---|---|---|---|---|---|---|---|---|
| 23/05/2015 | 38.67 | 22.70 | 10 | 3.9 | 19.88722946 | 47.53352259 | 0.418383246 | 4 |
| 24/09/2014 | 38.73 | 22.58 | 11 | 2.8 | 7.956556892 | 15.99558029 | 0.49742221 | - |
| 07/11/2014 | 38.30 | 22.11 | 19 | 4.8 | 65.59591897 | 115.8777356 | 0.566078709 | - |
| 26/01/2015 | 38.79 | 22.56 | 9 | 1.5 | 2.600117602 | 4.415704474 | 0.588834153 | - |
| 25/11/2014 | 38.76 | 22.53 | 11 | 1.6 | 3.335847798 | 4.875284901 | 0.684236484 | - |
| 27/01/2015 | 38.71 | 22.63 | 10 | 2.9 | 12.42311332 | 17.66037821 | 0.703445485 | 6 |
| 03/02/2015 | 38.80 | 22.50 | 14 | 1.4 | 2.8277366 | 3.999447498 | 0.707031809 | - |
| 27/10/2014 | 38.77 | 22.57 | 12 | 1.6 | 4.119218499 | 4.875284901 | 0.844918519 | 5 |
| 28/10/2014 | 39.10 | 22.37 | 88 | 3.8 | 37.1439635 | 43.05266105 | 0.862756508 | - |
| 09/02/2015 | 38.71 | 22.70 | 9 | 3 | 17.21818127 | 19.498446 | 0.883054028 | 6 |
| 10/10/2015 | 38.79 | 22.48 | 11 | 1.6 | 4.333529303 | 4.875284901 | 0.888877141 | - |
| 08/11/2014 | 38.73 | 22.58 | 7 | 2.2 | 7.956556892 | 8.830799004 | 0.901000791 | - |
| 31/03/2015 | 38.70 | 22.41 | 16 | 2.8 | 14.43804594 | 15.99558029 | 0.902627206 | 5 |
| 14/12/2014 | 38.62 | 22.88 | 18 | 3.7 | 35.77308422 | 38.99419867 | 0.917395034 | - |
| 08/09/2014 | 38.73 | 22.57 | 17 | 2.1 | 7.519341629 | 7.99834255 | 0.940112477 | - |
| 29/08/2015 | 38.73 | 22.45 | 11 | 2.3 | 9.624314282 | 9.749896377 | 0.987119648 | - |
| 26/10/2014 | 38.74 | 22.57 | 9 | 1.9 | 6.552714782 | 6.561452663 | 0.998668301 | - |
| 29/04/2015 | 38.71 | 22.60 | 7 | 2.4 | 10.76943128 | 10.76465214 | 1.000443966 | - |
| 12/01/2015 | 38.75 | 22.47 | 18 | 1.9 | 6.844012977 | 6.561452663 | 1.043063682 | - |
| 14/05/2015 | 38.71 | 22.59 | 12 | 2.3 | 10.30555047 | 9.749896377 | 1.056990769 | - |
| 22/09/2014 | 38.73 | 22.59 | 11 | 2 | 8.460302505 | 7.244359601 | 1.167846845 | - |
| 04/12/2014 | 38.71 | 22.57 | 16 | 2.1 | 9.547980932 | 7.99834255 | 1.193744938 | - |
| 13/07/2015 | 38.41 | 22.47 | 13 | 3.6 | 42.57455592 | 35.31831698 | 1.205452568 | 7 |
| 13/11/2014 | 38.72 | 22.58 | 10 | 2 | 8.909715747 | 7.244359601 | 1.229883142 | - |
| 01/11/2014 | 38.71 | 22.56 | 13 | 2 | 9.268213907 | 7.244359601 | 1.279369664 | - |
| 22/11/2014 | 38.73 | 22.59 | 10 | 1.9 | 8.460302505 | 6.561452663 | 1.289394733 | - |
| 09/10/2015 | 38.77 | 22.48 | 14 | 1.3 | 4.871392904 | 3.622429984 | 1.344785938 | - |
| 22/09/2014 | 38.76 | 22.34 | 20 | 2.5 | 16.80528255 | 11.88502227 | 1.413988309 | - |
| 10/09/2014 | 38.71 | 22.73 | 21 | 2.6 | 19.49205231 | 13.12199899 | 1.485448393 | - |
| 09/02/2015 | 38.70 | 22.70 | 10 | 2.5 | 17.81896494 | 11.88502227 | 1.499279053 | - |
| 03/08/2015 | 38.72 | 22.56 | 15 | 1.7 | 8.20684922 | 5.382697825 | 1.524672104 | - |

E: Distance between sample collection point and earthquake's epicentre, D: Strain radius

reports anomalies only from distant very large earthquakes. Authors do not mention any anomalies form nearby smaller seismic events. The thermal spring is also characterized by a large mean value of radon concentration. Note that the analysis by Das *et al.* (2006) does not use the empirical law of Dobrovolsky *et al.* (1979) and selects *ad hoc* seismic events.

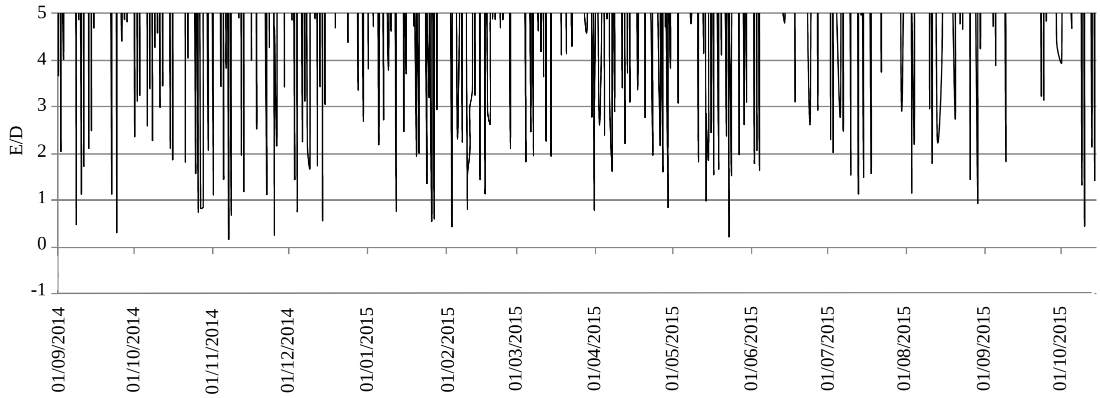


Fig. 8: Time evolution of E/D. It concerns seismic activity within 65 km

## CONCLUSION

The behavior of radon and of other physicochemical characteristics of Thermopylae natural thermal waters were analyzed in connection to local seismic activity. The integrated system proved able to effectively monitor, radio transmit and capture the measured variables. The most important outcomes from the statistical study of data, were the discovery of several periodicities, statistically significant correlations and radon anomalies. The statistical analysis suggests that there is a mixing of thermal underground waters with nearby sea waters. This explains why only radon anomalies were associated with local earthquakes.

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