**Management Systems
in
Production Engineering**

2015, No 2 (18), pp 51-57

DOI 10.12914/MSPE-01-02-2015

RADIATION ON MINING GROUNDS – CASE STUDY FORECASTING THE HAZARD LEVEL OF IONISING

Zygmunt KORBAN
Silesian University of Technology

Abstract:
When analyzing time series we can often observe that they have periodic oscillations (cyclic, seasonal). One of the methods which can be applied to investigate such a phenomenon and which belongs to the group of periodic components models is the method of harmonic analysis. The method consists in analyzing the oscillations around the medium level a_0 and building a model as the sum of so called harmonics. The paper presents the applicability potential of harmonic analysis in the forecasting process of radiation hazard on post-mining grounds (mine waters with raised content of radium Ra226 and Ra-228 drained off to the surface), using for that purpose the measurement results of radium concentration from the area of mine water catchment from the years 2004-2013.

Key words: *hazard of ionizing radiation, harmonic analysis*

INTRODUCTION

Ionizing radiation is one of the most characteristic phenomenon connected with atomic transitions taking place in atoms and in the atomic nucleus. The phenomenon consists in the separation of elementary negative charges (electrons) from atoms, which brings about the formation of the pairs of positive ions and electrons. The occurrence of ionizing radiation hazards is attributed to the presence of natural radioactive isotopes and cosmic radiation (radiation generated by the sun and galactic radiation) [4, 8]. Generally, we can distinguish three basic hazard sources:

- natural radioactive isotopes present in the Earth's crust,
- secondary cosmic radiation,
- radon and its decomposition products.

It is estimated that, statistically, within one year everybody is exposed to the radiation doze of around 2.0 mSv (in the member countries of the European Union the average doze generated by natural sources is at the level of around 3.0 mSv, and in Poland – 2.2 mSv) [3].

The radiation hazard posed by natural radioactive substances is classified into a group of natural hazards, whereof the sources are as follows:

- short-lived decomposition products of radon,
- gamma radiation containing radium,
- mine waters containing radium isotopes,
- sediments containing radium isotopes precipitated from mine waters containing radium.

The concentration of the potential energy of short-lived decomposition products of radon depends principally on the aeration method and extraction of the deposit. The concentration of radium in waters is increasing with depth (the salinity of waters is increasing then, which is a decisive factor)[1], and the occurrence of radioactive sediments is connected with the presence of barium (from such waters, radioactive sediments can precipitate at places where radium waters of the A type are getting mixed with waters containing sulphates) [10]. Due to the specific work environment (enclosed space, limited ventilation, etc.) the concentration of radium isotopes underground can several times surpass the concentration of radium in the open space (150 kB/m^3 in the coal mines of the Lower Silesia Coal Basin, 15 kBq/m^3 in the coal mines of the Upper Silesia Coal Basin and on average 8 B/m^3 in the open spaces [9]).

According to the executive regulations of the Geological and Mining Law, all underground mining plants in Poland are supposed to carry out periodic measurements of radiation hazard posed by natural radioactive substances. Only in 2007, coal mines carried out over 2900 measurements involving the concentration of potential energy of short-lived decomposition products of radon, 123 measurements of individual dozes of gamma radiation, 390 analyses involving the radioactivity of mine waters and 141 analyses of mine sediment samples. In compliance with the Regulation of the Minister of Economy on the occupational health and safety, mining activity and specialist fire protection equipment at underground mining plants, it is not acceptable that in a given year the hazard effected by natural radioactive substances in a coal mine should be higher than 20 mSv: underground workings being in the radiation hazard class B (workings in which the work environment creates potential hazard of being exposed to an yearly effective doze higher than 1mSv and not higher than 6 mSv) are treated as supervised workings, and the workings assigned

---

[1] we can distinguish waters of type A, containing radium and barium, and waters of type B, i.e. waters containing radium and sulphate ions.

to class A (workings in which work environment creates potential hazard of being exposed to an yearly effective dose higher than 6 mSv) – as controlled workings.

While in underground workings the main hazard source of ionizing radiation is made up by short-lived decomposition products of radon, with respect to surface areas located around coal mines, the said hazard is made up principally by mine waters with the raised content of radium and, to lesser degree – by solid mine wastes [7, 11].

In the coal mines of Upper Silesia Coal Basin there are strongly mineralized mine waters (with the content of salt exceeding 200 kg/m^3) having diversified concentration of radium isotopes. For example, in the south-western part of the Basin the content of radium 226 isotope reaches over a dozen kBq/m^3, and in the north-eastern part the content of radium 226 isotope is within the range from 0 to 6.8kBq/m^3. The total load of radium 226Ra isotope entering daily the workings is around 725 MBq and that of the 228Ra isotope – 700 MBq. However, only about 40% of radium present in mine waters stays in the underground workings in the form of sediments, and the remaining 60% of radium finds its way to the surface and then to rivers, bringing out contamination of the natural environment [6].

Since the coal mines are located in the upper course of the rivers Vistula and Odra, the salinification of these main rivers in Poland starts already in the initial sections of their course. The coal mines of Upper Silesia Coal Basin discharge every day to the rivers Vistula and Odra almost 900 thousand m^3 of water and the daily discharge of salt amounts to 11 thousand tons. The carried out research studies [9] emphasize also the impact of climate conditions (season of year) on the concentration of radium isotopes present in surface waters, which, particularly in the period of contrasting weather conditions (draught periods, heavy rainfall), contributes to periodic fluctuations in the summary concentration of Ra-226 and Ra-228 isotopes in mine waters (c_{Raw}).

The main objective of the paper is to present the applicability of one of the research methods used to investigate the phenomena of periodicity in time series (methods of harmonic analysis) in the prediction process involving the content of radium 226 isotope in the surface waters of mining areas. The calculation example (development of the model) is preceded by the discussion of the harmonic analysis itself (the method consists in building a model of periodic component as the sum of so called harmonics). As input data for the determination of the model, we applied the measurement results involving the concentration of Ra-226 recorded in the years 2004-2013 in one of water courses located in the area of the Upper Silesia Coal Basin.

HARMONIC ANALYSIS AS AN EXAMPLE OF PERIODIC COMPONENT MODEL

The method of harmonic analysis [2], apart from the method of indicators [12], or the Klein method [1] is one of many methods allowing for seasonal oscillations in the run of an investigated phenomenon. The method of harmonic analysis consists in building a model being a sum of so called harmonics – sinusoidal or cosinusoidal functions in the accepted period, with the first harmonic (*i* = 1) having the period equal to the length of the investigated period and the second (*i* = 2) being equal to a half of this period, etc. In the case of *n* observations, the number of all harmonics corresponds to the value *n/2*. The periodic component model of the series has the following form:

$$y_t = \alpha_0 + \sum_{i=1}^{\frac{n}{2}} \left[\alpha_i \sin\left(\frac{2\pi}{n} it\right) + \beta_i \cos\left(\frac{2\pi}{n} it\right) \right] \tag{1}$$

where:
i – number of harmonic,
α_0, α_i, β_i – parameters.

The values of parameters α_0, α_i, β_i are estimated by means of the least square method acc. to the following relations:

$$a_0 = \frac{1}{n}\sum_{t=1}^{n} y_t \tag{2}$$

$$a_i = \frac{2}{n}\sum_{t=1}^{n} y_t \sin\left(\frac{2\pi}{n} it\right) \qquad i = 1,2,\ldots,\frac{n}{2}-1 \tag{3}$$

$$b_i = \frac{2}{n}\sum_{t=1}^{n} y_t \cos\left(\frac{2\pi}{n} it\right) \tag{4}$$

where:
a_0, a_i, b_i – assessments of parameters α_0, α_i, β_i .
For the harmonic of the number

$$\frac{n}{2}: \quad a_{n/2} = 0, \qquad b_{n/2} = \frac{1}{n}\sum_{t=1}^{n} y_t \cos(\pi t). \tag{5}$$

For each of the harmonics, we determine the amplitude c_i

$$c_i = \sqrt{a_i^2 + b_i^2} \tag{6}$$

and the value of phase shift $\frac{\varepsilon_i}{\theta_i}$

where:

$$\varepsilon_i = arctg\left(\frac{a_i}{b_i}\right)$$

$$\theta_i = \frac{2\pi}{n} i$$

The procedures applied in the process of harmonic analysis are presented in Fig. 1.

CASE STUDY

The measurement results for one of the watercourses located in the area of Upper Silesia Coal Basin is presented in Fig. 2.

The values of statistics measures (selected random position measures) for the analyzed time period and for particular quarters are presented in Table 1.

The highest concentration values of radium 226 isotope in waters were recorded in the 3rd quarter of 2004 and 2007 – 0.17 [kBq/m^3]. Also the next highest values (0.14 [kBq/m^3] and 0.13 [kBq/m^3] were recorded in the 3rd quarters of 2009 and 2010 respectively.

The difference in the population of results (values of variability indices) for the first and third quarters is comparable and is considerably lower than that for the second and fourth quarters.

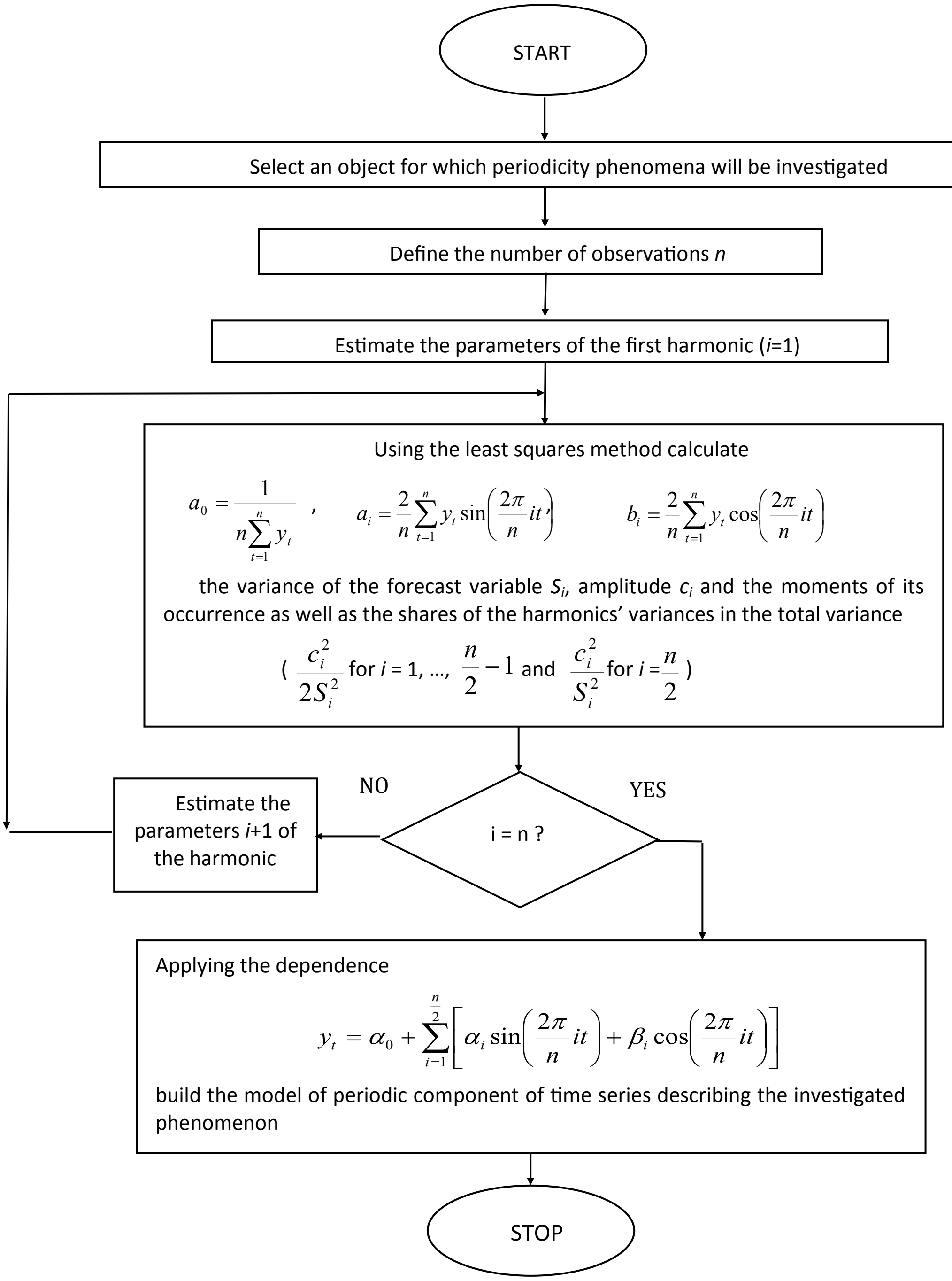

Fig. 1 Harmonic analysis – algorithm to follow
Source [5]

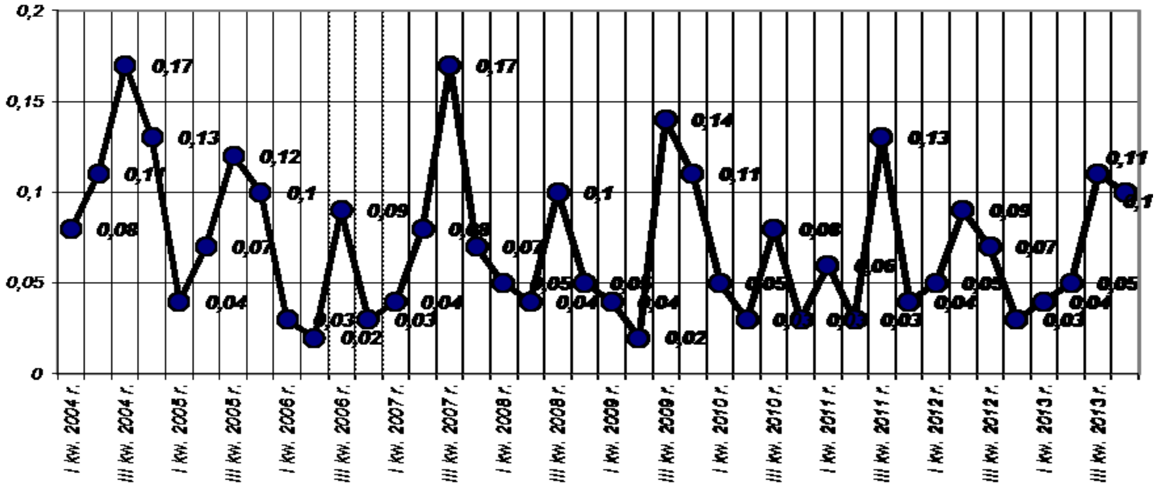

Fig. 2 Concentration of radium 226 isotopes in waters [kBq/m3] in a watercourse – measurement results

Table 1
Concentration of radium 226 isotopes in waters [kBq/m^3] in a watercourse – a set of selected random position measures

Measures of statistics	**Time period**				
	Years 2004-2013	**1st quarters in the years 2004 -2013**	**2nd quarters in the years 2004-2013**	**3rd quarters in the years 2004-2013**	**4th quarters in the years 2004-2013**
Maximum value x_{max} [kBq/m^3]	0.11	0.08	0.11	0.17	0.13
Minimum value x_{min} [kBq/m^3]	0.08	0.03	0.02	0.07	0.03
Median M_e [kBq/m^3]	0.095	0.05	0.04	0.12	0.05
Standard deviation S_x [kBq/m^3]	0.015	0.014	0.032	0.035	0.037
Variability index V_x [%]	15.8	28.0	58.2	29.3	55.8

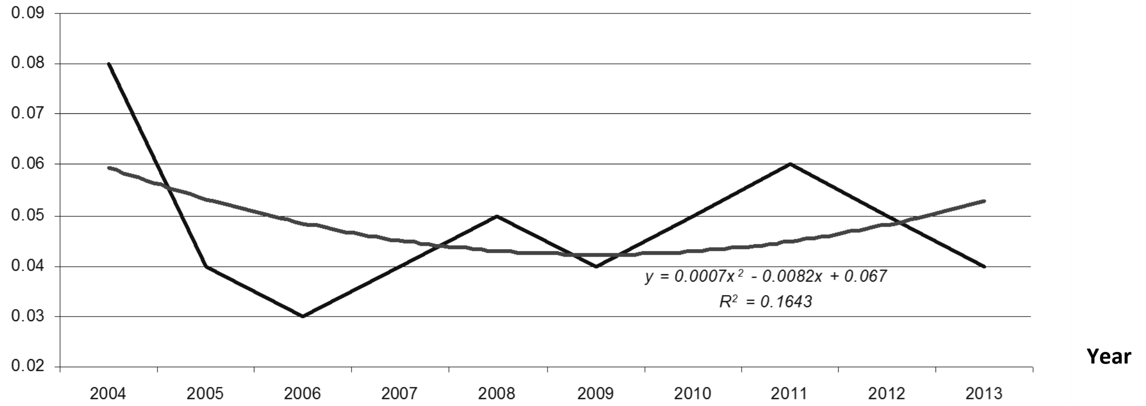

Fig. 3 Changes of radium isotopes concentration values in waters discharged to the environment in the 1rd quarters in the years 2004-2013

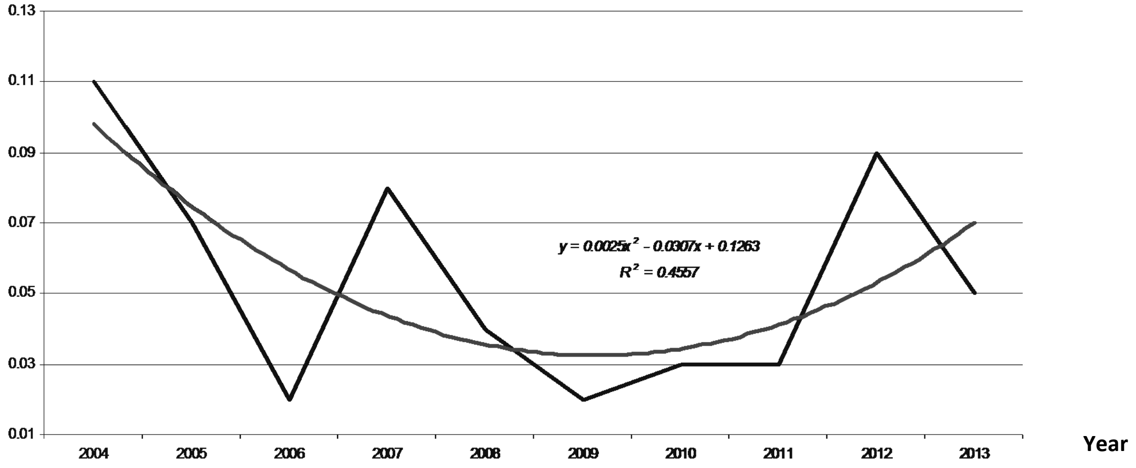

Fig. 4 Changes of radium isotopes concentration values in waters discharged to the environment in the 2rd quarters in the years 2004-2013

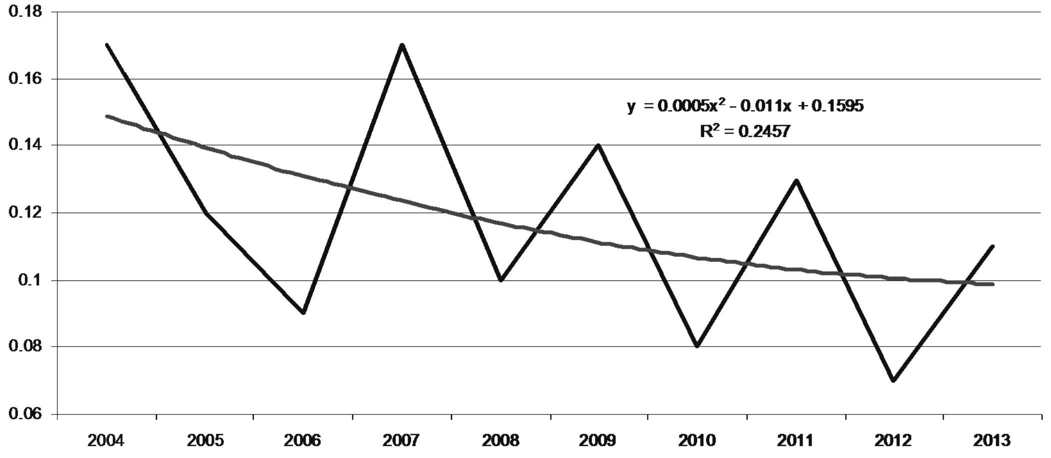

Fig. 5 Changes of radium isotopes concentration values in waters discharged to the environment in the 3rd quarters in the years 2004-2013

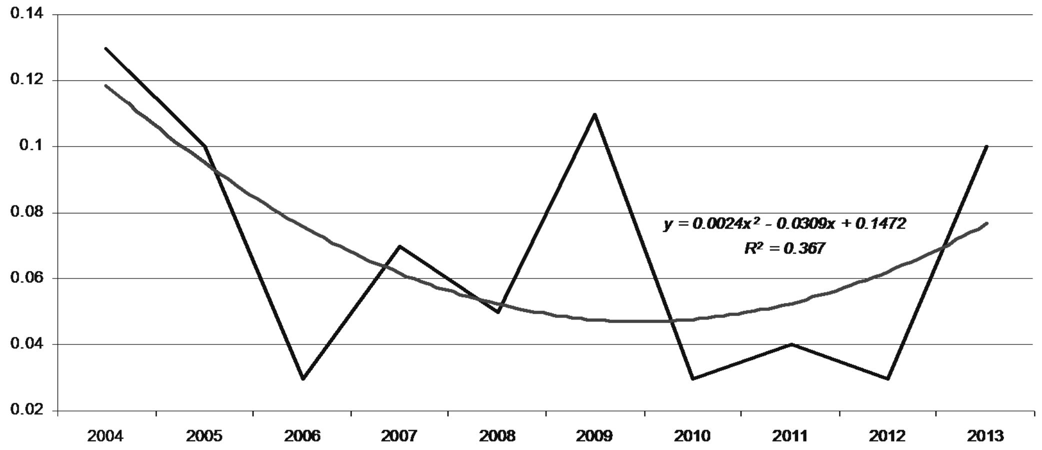

Fig. 6 Changes of radium isotopes concentration values in waters discharged to the environment in the 4rd quarters in the years 2004-2013

Table2
Values of parameters for successive harmonics

			for i = 1			
t	y_t	x	sin x	cos x	y_t sin x	y_t cos x
1	0.08	П/20	0.156	0.988	0.013	0.079
2	0.11	П/10	0.309	0.951	0.034	0.105
3	0.17	3П/20	0.454	0.891	0.077	0.151
4	0.13	П/5	0.588	0.809	0.076	0.105
5	0.04	П/4	0.707	0.707	0.028	0.028
…	…	…	…	…	…	…
…	…	…	…	…	…	…
37	0.04	37П/20	-0.454	0.891	-0.018	0.036
38	0.05	19П/10	-0.309	0.951	-0.015	0.048
39	0.11	39П/20	-0.156	0.988	-0.017	0.109
40	0.1	2П	0.000	1,000	0.000	0.100
			for i = 2			
1	0.08	П/10	0.309	0.951	0.025	0.076
2	0.11	П/5	0.588	0.809	0.065	0.089
3	0.17	3П/10	0.809	0.588	0.138	0.100
…	…	…	…	…	…	…
…	…	…	…	…	…	…
			…			
			for i = 20			
1	0.08	П	0.000	-1.000	0.000	-0.080
2	0.11	2П	0.000	1.000	0.000	0.011
3	0.17	3П	0.000	-1.000	0.000	-0.170
…	…	…	…	…	…	…
38	0.05	38П	0.000	1.000	0.000	0.050
39	0.11	39П	0.000	-1.000	0.000	-0.110
40	0.10	40П	0.000	1.000	0.000	0.100

The changing tendencies of radium isotopes concentration values in the waters discharged to the environment, broken down into particular quarters are presented in Fig. 3-6. Basing on the measurement results, the parameter a_0 = 0.072 was determined.

In order to determine a model describing the periodicity of a phenomenon, the parameters of successive harmonics were determined (Table 2). Aggregate values of particular harmonic parameters are presented in Table 3.

Basing on the calculated values, we can observe that the biggest parts of seasonal oscillations involve the 10th harmonic (it covers 39.4% of seasonal oscillations), and in this case the describing model has the following form:

$$\hat{y}_t = 0{,}072 - 0{,}035\sin\left(\frac{\Pi}{2}t\right) + 0{,}007\cos\left(\frac{\Pi}{2}t\right) \tag{7}$$

When we allow for the harmonics I, II, III, IV, V, VIII, X and XX, they cover 82.4% of seasonal oscillations, and the model describing the run of the phenomenon assumes the following form:

$$\hat{y}_t = 0{,}072 + 0{,}009\sin\left(\frac{\pi}{20}t\right) + 0{,}010\cos\left(\frac{\pi}{20}t\right) + 0{,}009\sin\left(\frac{\pi}{10}t\right) + \\ + 0{,}011\cos\left(\frac{\pi}{10}t\right) + 0{,}014\sin\left(\frac{3\pi}{20}t\right) + 0{,}004\cos\left(\frac{3\pi}{20}t\right) + 0{,}012\sin\left(\frac{\pi}{5}t\right) - \\ - 0{,}009\cos\left(\frac{\pi}{5}t\right) - 0{,}002\sin\left(\frac{\pi}{4}t\right) + 0{,}015\cos\left(\frac{\pi}{4}t\right) - 0{,}012\sin\left(\frac{2\pi}{5}t\right) + \\ + 0{,}001\cos\left(\frac{2\pi}{5}t\right) - 0{,}035\sin\left(\frac{\pi}{2}t\right) + 0{,}007\cos\left(\frac{\pi}{2}t\right) - 0{,}011\cos(\pi t) \quad (8)$$

The aggregate list of oscillation amplitudes for the above harmonics and the values of their phase shift are presented in Table 4.

Basing on the determined model, we can predict the concentration of radium Ra-226 in surface waters of the investigated water course, assuming respectively: for the first quarter of 2014 – t = 41, for the second quarter of 2014 – t = 42, etc. (an exemplary prediction of the concentration of radium isotopes in waters for the 2nd quarter of 2014 is 0.106 $\left[\frac{kBq}{m^3}\right]$.

CONCLUSIONS

Due to the occurring radiation hazards posed by natural radioactive substances, mining plants are obliged to carry out a seasonal control of four parameters describing this hazard: the concentration of potential energy alpha in the air of short-lived decomposition products of radon, exposition to the external gamma radiation, summary concentration of radium Ra-226 and Ra-228 isotopes in mine waters and summary specific activity of radium Ra-227 and Ra-228 isotopes present in mine sediments. The results of these measurements show that more and more frequently, natural radioactive substances are also found on the surface (side effects of the carried out excavation process). While in the case of underground mining workings the main hazard source of ionizing radiation is attributed to short-lived decomposition products of radon, on the surface area the highest hazard is connected with the occurrence of mine waters of the raised content of radium (Ra-226, Ra-228). In the case of the latter, characteristic is the periodicity involving the concentration changes of the content of radium isotopes.

Table3
Aggregate values of harmonic parameters

	i = 1	i = 2	i = 3	i = 4	i = 5
a_i	0.009	0.009	0.014	0.012	-0.002
b_i	0.010	0.011	0.004	-0.009	0.015
$c_i^2/2s^2$	0.053	0.061	0.065	0.069	0.067
	i=6	i=7	i=8	i=9	i=10
a_i	0.006	0.004	-0.012	-0.001	-0.035
b_i	-0.003	-0.005	0.001	-0.009	0.007
$c_i^2/2s^2$	0.015	0.012	0.044	0.025	0.394
	i=11	i=12	i=13	i=14	i=15
a_i	0.004	0.009	-0.002	0.001	-0.006
b_i	0.002	0.004	0.003	0.007	0.000
$c_i^2/2s^2$	0.007	0.031	0.004	0.013	0.012
	i=16	i=17	i=18	i=19	i=20
a_i	0.001	0.003	-0.004	-0.004	0.000
b_i	-0.007	-0.003	0.003	0.008	-0.011
$c_i^2/2s^2$	0.015	0.007	0.007	0.028	0.071

Table4
Oscillation amplitudes for the harmonics I, II, III, IV, V, VIII, X and XX and their phase shift values

Harmonica	Oscillation amplitudes	Values of phase shift
I	0.013	4.665
II	0.014	2.183
III	0.015	2.743
IV	0.015	-1.476
V	0.015	-0.169
VIII	0.012	-1.184
X	0.036	-0.874
XX	0.011	0.000

The seasonal growths or drops of radium isotopes concentration are effected among others by climatic phenomena characteristic for particular year seasons: draught (mainly in summer) and intensive rainfall (mainly in spring, autumn and winter) – the correlation coefficient between the values of radium isotope concentrations present in the waters of the investigated water course and the average atmospheric rainfall values for the towns of Żory, Murcki and Bieruń Stary in the years 2012 and 2013 is distinct and has the value of – 0.35.

The paper presents practical applicability of the harmonic analysis in the forecasting of the isotopes of radium Ra-226 in surface waters. The method of harmonic analysis belongs to a group of methods which can be applied to analyze time series and which is based on the model built in the form of so called harmonics – sinusoidal or cosinusoidal functions in the accepted time period. Although the number of harmonics should be possibly the largest (the longer the time series the larger the number of harmonics), yet when building the models, we apply only the harmonics whose share in the explanation of the variance of the investigated variable is the highest. In the example presented in the paper, 20 harmonics were defined (the measurement results were analyzed from January 2004 to December 2013), but only eight of them were applied for the forecasting process, i.e. the harmonics I, II, III, IV, V, VIII, X and XX. The harmonics are explaining in total over 80% of variances of the forecast variable, with the harmonic X covering as much as 39.4% of seasonal oscillations.

REFERENCES

[1] C. Almon C. "The INFORUM approach to interindustry modeling". *Economic Systems Research*, vol. 3, pp. 1-7, Nr 1, 1991.

[2] M. Cieślak, P Dittmann P, J. Krupowicz, I. Kuropka, D. Kwiatkowska-Ciotucha, B. Radzikowska, J. Szanduła, U. Załuska. *Prognozowanie gospodarcze. Metody i zastosowania*. Warszawa, Wydawnictwo Naukowe PWN, Wydanie czwarte zmienione, 2005, pp. 88-89.

[3] B. M. R. Green, J. S. Huges, P. R. Lomas. Radiation Atlas – Natural Sources of Ionising Radiation in Europe, prepared for: Directorate-General for Environment, Nuclear Safety and Civil Protection, Commission of the European Communities, 1997.

[4] W. Heinrich, S. Roesler S, H. Schraube. "Physics of cosmic radiation fields". *Radiation Protection Dosimetry*, vol. 86, pp. 253-258, Nr 4, 1999.

[5] Z. Korban. „Wykorzystanie analizy harmonicznej w procesie prognozowania poziomu zagrożenia promieniowaniem jonizującym na terenach górniczych". *Górnictwo i Geologia*. Zeszyt 1, Tom 6, pp. 121-129, 2011.

[6] J. Lebeckam. "Monitoring of Radiation Exposure from Different Natural Sources in Polish Coal Mines". *Int. Conf. on Occupational Safety in Mining*, vol. 2, Toronto, p. 408, 1985.

[7] J. Lebecka, S. Chałupnik, B. Łukasik, M. Wysocka. "Monitoring and control of radioactive contamination of natural environment caused by mining activity," in *Proc. of Int. Conference Ecological Aspects of Underground Mining*, 1993, p. 198.

[8] B. J. Lewis. "Cosmic radiation exposure on Canadian-based commercial airline routes". *Radiation Protection Dosimetry*, vol. 86, pp. 7-24, Nr 1, 1999.

[9] J. Skowronek J. (red.): Zagrożenia naturalnymi źródłami promieniowania jonizującego w przemyśle wydobywczym. Główny Instytut Górnictwa. Katowice 2007, pp. 183-201.

[10] I. Tomza, J. Lebecka. Radium Bearing Waters in Coal Mines. Proc. of Int. Conf. on Radiation Hazard in Mining. Golden, Colorado, USA, American Institute of Mining, Metallurgy and Petroleum Engineers Inc. 1981.

[11] J. Zgadaj, K. Skubacz, S. Chałupnik: The influence of radon and it's progeny emitted from exhaust shafts of coal mines on the contamination of the outdoor air. Proc. of International Conference Technologically Enhanced Natural Radioactivity-TENR '96. Główny Instytut Górnictwa . Katowice 1996.

[12] K. Zając. *Zarys metod statystycznych.* Warszawa*,* PWE, 1988.

dr inż. Zygmunt Korban
Silesian University of Technology, Faculty of Mining and Geology
ul. Akademicka 2a, 44-100 Gliwice, POLAND
e-mail: zygmunt.korban@polsl.pl

Artykuł w polskiej wersji językowej dostępny na stronie internetowej czasopisma.

The article in Polish language version available on the website of the journal