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Modelling benzo(a)pyrene concentrations for different meteorological conditions – Analysis of lung cancer cases and associated economic costs

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ABSTRACT

Air pollution originating from the household presents a significant burden to public health, especially during the wintertime in countries, such as Poland, where coal substantially contributes to the energy market. One of the most hazardous components of particulate matter is benzo(a)pyrene (BaP). This study focusses on the impact of different meteorological conditions on BaP concentrations in Poland and associated impacts on human health and economic burdens. For this study, we used the EMEP MSC-W atmospheric chemistry transport model with meteorological data from the Weather Research and Forecasting model to analyze the spatial and temporal distribution of BaP over Central Europe. The model setup has two nested domains, with the inner domain at 4 km × 4 km over Poland, which is a hotspot for BaP concentrations. The outer domain covers countries surrounding Poland in coarser resolution (12 × 812 km), to ensure that transboundary pollution is properly characterized in the modelling. We investigated the sensitivity to variability in winter meteorological conditions on BaP levels and impacts using data from 3 years: 1) 2018, which represents average meteorological conditions during the winter season (BASE run), 2) 2010 with a cold winter (COLD), and 3) 2020 with a warm winter (WARM). The ALPHA-RiskPoll model was used to analyze the lung cancer cases and associated economic costs. The results show that the majority of Poland exceeds the target level of benzo(a)pyrene (1 ng m^{-3}) mainly due to high concentrations during the cold months. High concentrations of BaP have serious health implications and the number of lung cancers in Poland due to BaP exposure varies from 57 to 77 cases for the WARM and COLD years, respectively. It is reflected in the economic costs, which ranged from 136, through 174 to 185 million euros/year for the WARM, BASE and COLD model runs, respectively.

1. Introduction

Air pollution is a widespread problem that poses a serious threat to human health and life throughout the world (Anioł et al., 2021). Polycyclic aromatic hydrocarbons (PAHs) are a group of substances, many of which exhibit toxic, teratogenic, mutagenic, and carcinogenic properties (Schreiberová et al., 2020). They are common in the atmosphere in areas where solid and liquid fuels are used and they have the physicochemical properties of persistence, semivolatility and bioaccumulation (Cao et al., 2021). Monitoring networks tend to focus on one PAH, benzo(a)pyrene (BaP), as a representative of the group. The International Agency for Research on Cancer (IARC) classified BaP as carcinogenic to humans (Group 1) and the majority part of the other PAHs as possibly carcinogenic to humans (Group 2B) (IARC, 2010). To protect human health, the EU's air quality directive (Directive 2004/107/EC, 2004) sets a target value (TV) for annual mean BaP concentrations in ambient air equal to 1 ng/m^3. This TV is very high compared to an estimated reference level of 0.12 ng/m^3, assuming the WHO unit risk of lung cancer, and an acceptable additional lifetime cancer risk of approximately 1×10^{-5} (de Leeuw and Ruyssenaars, 2011). According to the EU Directive 2004/107/EC, BaP should be used as a marker of the carcinogenic risk of PAHs in ambient air. The main exposure route of BaP and other PAHs is

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inhalation, and the lung is the main target organ for exposed contaminants. Therefore, many studies are being conducted that analyze the association between BaP and respiratory diseases, especially lung cancer (Cao et al., 2021). PAHs also affect fetal development, causing a reduction in the weight of the newborn at birth, and probably have a negative effect on the cognitive development of young children (Schreiberová et al., 2020). Long-term exposure to PAH has been associated, in addition to lung cancer, to other health endpoints such as increased incidence of skin and bladder cancer (Boada et al., 2015). Exposure to PAH in early-life might play a role in ADHD behavior problems (Perera et al., 2014). High concentrations, such as those found in some occupational situations might lead to fatal ischemic heart diseases (Mallah et al., 2021).

The European Environment Agency estimates that in 2017 ca. 17% of urban dwellers in member states of the European Union were exposed to an annual average target concentration of BaP in excess of the limit specified in Directive 2004/107/EC (Schreiberová et al., 2020). In urban areas, the main sources of BaP are domestic coal and wood heating and transport (so-called "low emissions";(Kumar et al., 2020)). Other significant sources of benzo(a)pyrene are thermal power plants, heavy industry (especially aluminium smelters), factories, uncontrolled fires and low-temperature waste burning, waste incineration, and volcanic eruptions (Kumar et al., 2020).

Poland is the country with the highest BaP concentrations in Europe, with the TV exceeded by several hundred percent (Supreme Audit Office, 2018). The main emission sources of BaP in Poland are combustion of coal and biomass, mostly in domestic boilers, in areas of single-family housing (Widziewicz et al., 2017). High BaP concentrations, far exceeding the target value, occur not only in large cities, but also in small towns and villages (CIEP, 2018). The Polish National Cancer Registry (PNCR) noted that lung cancer is now the most common cause of death, replacing breast cancer in that infamous position. Each year, lung cancer accounts for about 30% of all cancer deaths among men and about 15% among women (Widziewicz et al., 2017). A high correlation has been found between BaP concentrations and cases of all cancers in the Lower Silesia area in Poland (Tuśnio et al., 2020).

Given the significant environmental problem of the existence of BaP in the atmosphere, more studies are needed to better understand BaP concentrations in terms of their temporal and spatial distribution and their impact on the population's health using air quality modelling and assessment techniques. This study shows the population exposure to BaP concentrations in Poland, which is the area with the highest BaP concentrations in Europe. We analyse the potential impact of winter severity based on the different meteorological conditions used for modelling, in area with a large share of residential combustion, on BaP concentrations and exceedances of the critical level. The analysis of lung cancer cases and associated economic costs due to high concentrations of BaP in the largest cities in Poland are presented. The current political situation and the fuel crisis (as of 2022) make this problem even more acute, as, for instance, the previous Polish regulations towards the cleaner air were postponed, which will have an adverse impact on air quality in Central Europe.

2. Data and methods

2.1. The EMEP4PL model simulations

We used the EMEP MSC-W rv4.34 complex Eulerian chemical transport model which has been described in detail in Simpson et al. (2012), Pommier et al. (2020) and Pommier (2021). The Meteorological Synthesizing Centre-West (MSC-W) of the European Monitoring and Evaluation Program (EMEP) has been performing calculations with this model in support of the Convention on Long Range Transboundary Air Pollution, which makes the model a one of the key tools within the European air pollution policy assessments (Status EMEP Report, 2022). The model is already in use in a forecasting mode as one of the ensemble members of the MACC/CAMS daily ensemble production system for regional air quality forecasting (Marécal et al., 2015). Traditionally, the model has been run for all of Europe at 50 km × 50 km, however it has been successfully applied at a higher spatial resolution (e.g. 5 km × 5 km or 1 km × 1 km) for the UK (EMEP4UK) (Lin et al., 2017; Vieno et al., 2010, 2014) and the Netherlands (EMEP4NL) (van der Swaluw et al., 2021). The example applications of the EMEP MSC-W model covers: modelling of surface ozone during a heat-wave in the UK (Vieno et al., 2010), specifying the role of long-range transport in determining air pollution concentrations and source-receptor simulations for the European and country scales (Ots et al., 2016; Pommier et al., 2020; Wind et al., 2020) or. The first application of EMEP MSC-W over Poland (EMEP4PL) is described by Werner et al. (2018). Here, the model was extended towards BaP modelling as nonreactive particles, which is a similar approach as previously used by Schreiberová et al. (2020) with the CAMx model.

The EMEP4PL meteorological driver is the Weather Research and Forecasting (WRF) model version 4.3.1. The WRF and EMEP4PL models have the same configuration of domains. We used two one-way nested domains - the outer domain covers Europe at a 12 km × 12 km grid (d01), and the inner domain is focused on Poland at a 4 km × 4 km resolution. Parameterisation of the meteorological WRF model follows the setups described in (Werner et al., 2018). These include the Noah Land Surface Model (Chen and Dudhia, 2001), Mellor-Yamada-Janjic boundary layer physics (Nonsingular implementation of the Mellor–Yamada level 2.5 scheme in the NCEP meso model. National Centers for Environmental Prediction, 2001), RRTMG long- and short-wave radiation scheme (Iacono et al., 2008), Grell 3D cumulus parameterisation with radiative feedback and shallow convection (Grell, 2002), and the Morrison double-moment microphysics scheme. The simulation was driven by the NCEP FNL Operational Global Analysis data with a horizontal resolution of $1^\circ \times 1^\circ$, 27 vertical levels and temporal resolution of 6 h. The WRF was run with the observational nudging turned on for the air temperature (T2), moisture (RH), and wind components (WS). Observation data were taken from the NCEP Automated Data Processing global surface observational weather data which include land and marine surface reports received via the Global Telecommunications System.

We used a high resolution (1 km × 1 km) national emission database for Poland provided by the Institute of Environmental Protection – National Research Institute (IEP-NRI) and the EMEP 0.1° x 0.1° database (https://www.ceip.at/) outside of the Polish area. The EMEP model reads annual emissions, which are entered in the model by months, days of the week, and hours of the day according to the EMEP time factors (Simpson et al., 2012). The factors are specific to each pollutant, emission sector, and country, and thus reflect the different climates and energy-use patterns in different parts of Europe. The emissions were distributed in 7 vertical layers according to the SNAP sectors. The vertical distribution was based on (Bieser et al., 2011). The heating degree-day concept was used to derive emissions from the residential sector from air temperature (Simpson et al., 2012).

The IEP-NRI emission inventory is a part of the national air quality modelling system, which uses the GEM-AQ model (Kaminski et al., 2008). The modelling results serve as supplements for in-situ AQ monitoring, which constitutes the basis of the Chief Inspectorate for Environmental Protection (CIEP) Air Quality Annual Assessments. The IEP-NRI emission inventory used here follows the methodology described in (Gawuc et al., 2021).

Three yearly simulations were run with EMEP4PL. For each, the same emission data was used, but the meteorological conditions were altered. For the BASE simulation, we used meteorological data for the year 2018. The BASE simulation was verified by comparison with observations of BaP concentrations (see Section 2.2). Then, we analysed meteorological conditions for the years 2010–2020 and based on the mean air temperature for the winter months, we selected a year with a cold winter (2010 – "COLD") and a warm winter (2020 – "WARM").

Winter meteorological conditions for 2018 were average for the analysed period of 2010 – 2020.

2.2. Model verification

Observations of BaP concentrations in Poland are carried out by the Chief Inspectorate of Environmental Protection (CIEP). Measurement data of BaP concentrations were using the gravimetric method of dust collectors. Every two weeks, 14 disposable filters are inserted into the sampler, which the device automatically changes every 24 h. After 14 days, all filters are removed, placed in special transport containers, and transported to the laboratory. The filters obtained from the dust samplers are also used for the determination of polycyclic aromatic hydrocarbons, including benzo(a)pyrene. Due to the inhomogeneity of the measurement data with a time step of 24 h, the data from 120 CIEP stations were aggregated to 7-day average concentrations throughout the year. To compare model results with observations, we aggregated modelled 1-hour BaP concentrations for the year 2018 to 7-days values and calculated mean statistics such as: Mean Bias (MB), Mean Gross Error (MGE), Normalised Mean Bias (NMB), Normalised Mean Gross Error (NMGE) and Index of Agreement (IOA).

2.3. Health analysis and economic costs

All cities in Poland with a population of more than 200,000 people (14 cities) were selected to analyze lung cancer cases and associated economic costs due to BaP concentrations. These cities correspond to 1% of Poland's area and 19% of the total population. The study was based on modelled results for the BASE, COLD and WARM runs and concentrations from measuring stations for the same years. We used the AlphaRiskpoll tool created by Holland & Spadaro to analyze the number of additional lung cancer cases (ALCC), distinguishing between fatal and non-fatal cancers. Relative risk calculations were based on the Toxicological Review of Benzo[a]pyrene report presented by the United States Environmental Protection Agency in 2017. The unit risk of inhalation was set at 6 × 10–4 per μg/m^3, which was calculated by linear extrapolation (slope factor = 0.1/BMCL10) from the BMCL10 of 0.16 mg/m^3 for the incidence of upper respiratory and upper gastrointestinal (stomach) tumors in male hamsters chronically exposed by inhalation to BaP (Thyssen et al., 1981). The risk factor for the ALCC as a result of exposure to BaP was determined to be 8.7×10^{-5} per 1 ng/m^3 per person, which was calibrated for exposure over a 70-year life. The risk factor for the ALCC as a result of BaP exposure was determined to be 8.7×10^{-5} per 1 ng/m^3 per person (WHO, 1987, 2000), which was calibrated for exposure over a 70-year lifetime based on observations on coke-oven workers in the USA corrected for the fraction of BaP in benzene soluble coke-oven emissions. Although this relationship was published some time ago, it is still accepted and used by WHO, for example in the AirQ+ model of WHO (2020). Based on this function, the number of lung cancer cases per 1 ng/m^3 per person in 1-year equates to 1.2×10^{-6}. BaP concentrations were multiplied by population for each city (Schucht et al., 2020). To determine deaths from BaP exposure, the survival rate for lung cancer was taken from the European Cancer Information System and set at 19% based on reported incidence of 318,000 cases and 257,000 deaths in the EU27 in 2020 (ECIS, 2019), indicating the high mortality rate associated with the disease after diagnosis. However, it is envisaged here that survival rates may move to the European average on a timescale consistent with the latency between exposure and development of lung cancer, for which a figure of 13.6 years has been adopted, consistent with methods used for the European Environment Agency (Schucht et al., 2021) and the review of Lipfert and Wyzga (2019). Lipfert and Wyzga defined a range of 10 to 30 years for latency, demonstrating the uncertainty associated with this parameter. Also, when studying the estimation of the length of time between the biological initiation of cancer and diagnosis by developing a Weibull-type survival model, the exact period for lung cancer is indicated as 13.6 years. Furthermore, statistical analysis showed an identical exact and modelled lung cancer latency period (Nadler and Zurbenko, 2014). A sensitivity analysis was carried out here and demonstrated that the use of the current Polish mortality rate associated with lung cancer would increase the economic valuation of impacts by 14%. Different assumptions on latency period using the range for lung cancers from Lipfert and Wyzga would increase damage by 11% (reducing latency to 10 years) or increase damage by 38% (increasing latency to 30 years). The model takes into account the age structure of the population and its projection based on data from Eurostat by according to NUTS3 regions. The gender and age structure is not included in the modelling.

To quantify the economic costs associated with health impacts from BaP, the value of statistical life, that is, the rate of tradeoff between wealth and risk, was set at €3.9 million, based on meta-analysis of revealed preference studies on mortality valuation by OECD (2012). The value of cancer morbidity at €491,000 was determined by the ECHA (2016). The value of a non-fatal cancer at €130,000 based on Nedellec and Rabl (2016) and Hofmarcher et al. (2020). Emphasis is placed on public reference in the valuation, enabling the inclusion of the loss of utility/quality and length of life for the patient. Account of lost utility for close relatives and friends was not included in the valuation. Data were adjusted for a latency period for lung cancer set at 13.6 years (Schucht et al., 2020), projected economic growth of 1% per year, and an annual discount rate of 4% (Schucht et al., 2021).

3. Results

3.1. Model evaluation for the BASE year

The statistical measures for the comparison of the modelled and measured data are summarised in Table 1. Mean Bias (MB) indicates that the model has a tendency to underestimate measured BaP concentrations (MB = −2.22 ng m^{-3}). Mean Gross Error (MGE) (2.66 ng m^{-3}) is slightly higher than the absolute value of MB, therefore there are some periods or some stations for which the model overestimates concentrations. Normalised Mean Bias (NMB) is negative for all seasons and the highest underestimation is in autumn. Mean annual Index of Agreement (IOA) is equal to 0.69.

The time series of the modelled and observed BaP concentrations (Fig. 1) show that the model correctly reproduces the temporal variability of BaP concentrations during the year. The greatest variations between modelling results and measurements occur during the heating season, when BaP concentrations are the highest. Despite greater differences in the autumn–winter period, the model captures the episodes with high BaP concentrations.

3.2. Modelled temporal and spatial variability of BaP concentrations over Poland for the BASE, COLD and WARM run

For half of the year (from November to April) mean monthly BaP concentrations are above the value of 1 ng m^{-3}, independent of whether it is a year with a cold or warm winter (Fig. 2). For each of the analysed years, the highest concentrations are from December to March and exceed for this period 4 ng m^{-3} for the cold year and 2 ng m^{-3} for the warm year. The month with the highest concentrations varies between the analysed years (2010, 2018, 2020) and depends on the course of winter air temperature for the individual year. In general BaP concentrations in summer months are around 30 and 20 times lower compared

Table 1
Statistical measures for model-measurements comparison for 7-days mean BaP concentrations for Poland (120 stations) for 2018.

FAC2	MB	MGE	NMB	NMGE	RMSE	R	IOA
0,44	−2,22	2,66	−0,52	0,62	5,51	0,67	0,69

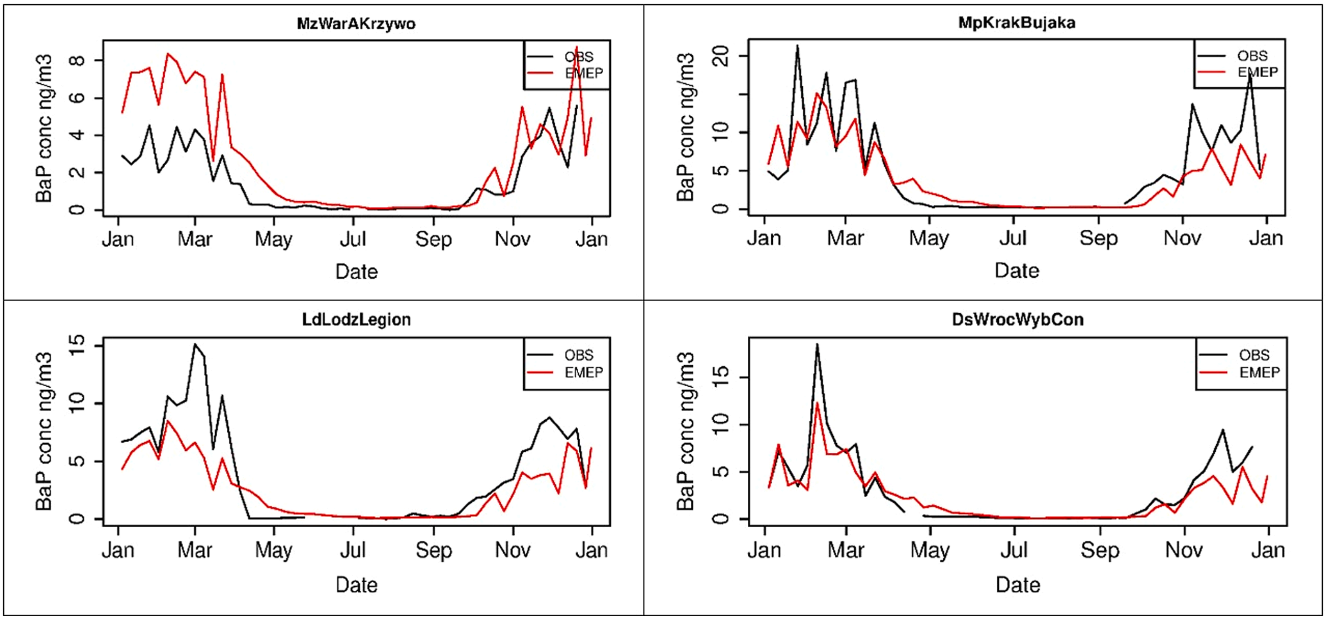

Fig. 1. Time series of modelled and observed BaP concentrations in 2018 in Warszawa, Krakow, Lodz and Wroclaw, respectively.

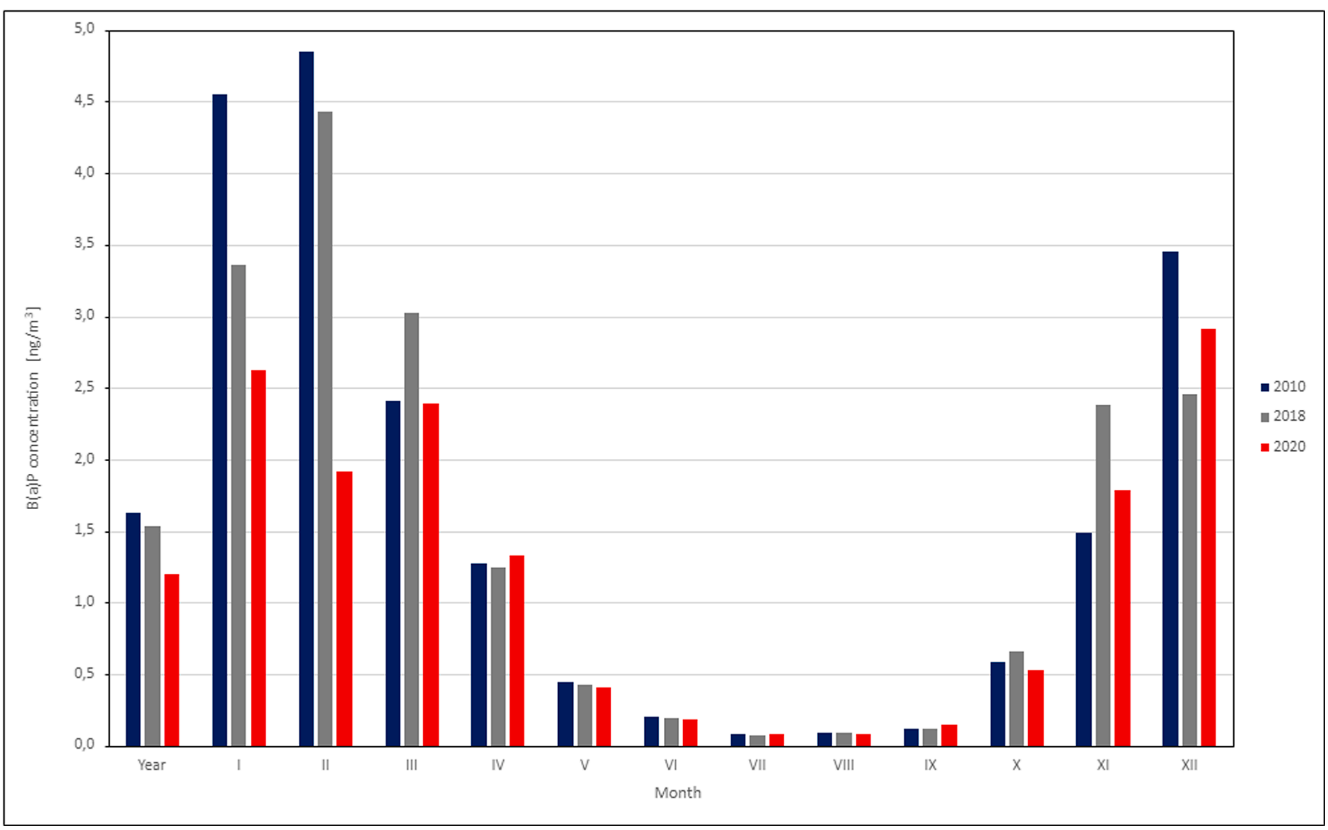

Fig. 2. The mean BaP concentrations in the COLD, BASE and WARM run in Poland.

to winter for the cold and warm year, respectively.

The annual mean spatial distribution shows the highest BaP concentrations in southern Poland (Upper Silesia) and in the largest cities (Fig. 3). BaP concentrations in these areas exceed 3 ng m^{-3} for the year 2010 and 2 ng m^{-3} for the year 2020. Lower BaP concentrations are in less populated areas, such as north-western and eastern Poland and in the mountainous area in the south.

Our results show a significant impact of meteorological conditions on BaP concentrations in Poland. For almost the whole country, BaP concentrations in 2010 were higher than in 2020 (Fig. 4). For most of the area, BaP concentrations in the COLD year are at least 20–40% higher than in the WARM year; whereas for western Poland it is even more than 50% higher in 2010 compared to 2020. Differences are linked only to variation in weather conditions, as emissions data are (artificially) kept the same across the scenarios. Factoring in increased emissions during colder periods would further increase the difference between the COLD

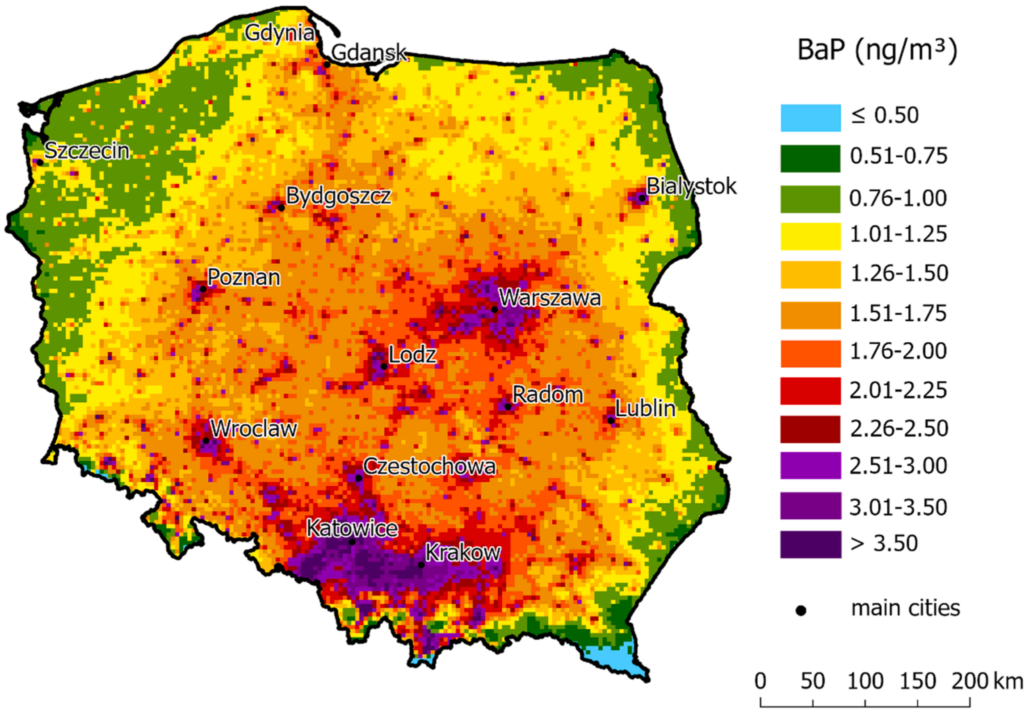

Fig. 3. Annual mean spatial distribution BaP concentrations in 2018 in Poland.

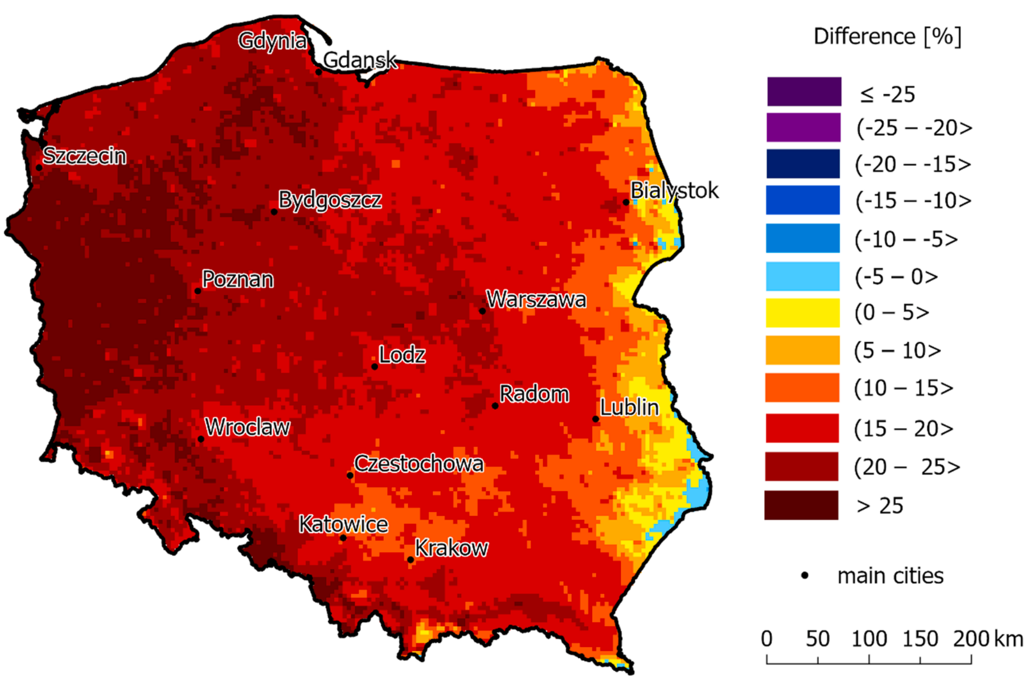

Fig. 4. Comparison of BaP concentrations based on meteorological conditions in 2010 to 2020 in Poland.

and WARM year.

High inter-annual variability of BaP concentrations was previously reported by Albuquerque et al. (2016) for Porto in Portugal and by Schreiberová et al. (2020) for the Czech Republic area. This emphasizes that variability in meteorological parameters has to be included when the impact of regulations on BaP concentrations and limit exceedances are considered.

3.3. Exceedances of BaP concentrations and health & economic implications

Our modelling estimates that the EU target annual level of 1 ng m^{-3} is exceeded for 91% of Polish area in 2010 and for 64% area in 2020 (Fig. 5). For December-March, the value of 1 ng m^{-3} is exceeded for 98% of the country for the COLD and BASE year and for above 85% area for the WARM year. The results for the BASE and COLD year show that approximately 98% of the Polish population is exposed to BaP concentrations above the target annual level of 1 ng m-3 and that more than

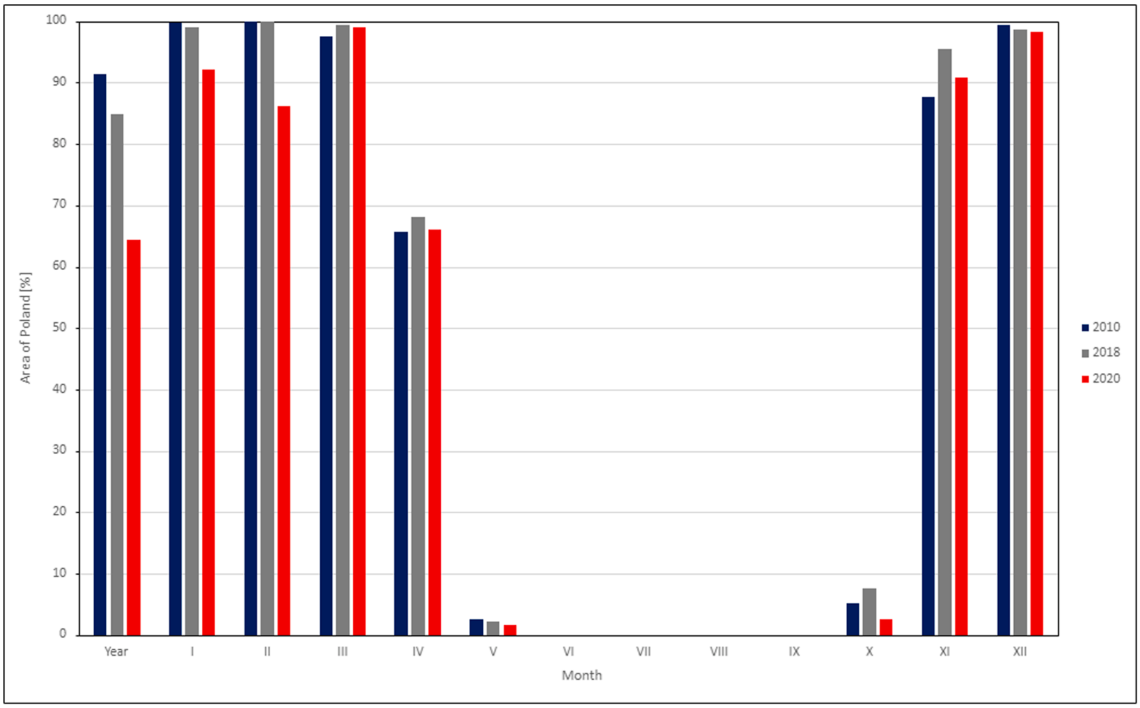

Fig. 5. Area of BaP concentrations above 1 ng m^{-3} in the COLD, BASE and WARM run in Poland.

50% of the population is exposed to a value at least two times higher. For the WARM year it is about 90% of population that is exposed to exceeded BaP concentrations (Table 2).

It is worth noting that in the case of the capital city of Poland, unlike other cities, the values indicated by measurements are significantly lower than those indicated by modelling. Observation sites may be influenced by a particular emission source, which causes concentrations to differ from the grid average from the model, consequently affecting health analyses (Holnicki and Nahorski, 2015). It is worth pointing out the differences between Katowice and Gdynia, which are similar in terms of population, but differ in geographic location: Katowice located in the Upper Silesian industrial region, and Gdynia on the coast. The number of cases indicated by the model for the BASE year is almost 2.5 times greater for Katowice, and considering the measurements, this difference is more than 4 times greater in the COLD year.

Based on the mean modelling result for each grid square in Poland, using the AlphaRisk tool we have calculated the total number of lung cancer per year. Values of 73, 77 and 57 were obtained for the BASE, COLD and WARM run, respectively (Table 3). 80% of all these cases are fatal cancers.

Table 2
Population exposure for BaP annual mean concentrations for the year 2010, 2018 and 2020.

Total Population	BaP, year, annual average, exposed population (%)				
	<TV		>TV		
	<0.12 ng m^{-3}	0.12–1 ng m^{-3}	1–2 ng m^{-3}	2–4 ng m^{-3}	>4 ng m^{-3}
37 972 812	**2018**				
	0	949 320	15 732 136	19 912 943	1 378 413
	0	2.50	41.43	52.44	3.63
	2010				
	0	713 889	13 928 427	21 879 935	1 450 561
	0	1.88	36.68	57.62	3.82
	2020				
	0	3 899 808	21 576 152	12 196 867	299 985
	0	10.27	56.82	32.12	0.79

Table 4 presents the adjusted economic burdens for latency for cities in Poland over 200,000 inhabitants and the whole country. Considering the results of the modelled concentrations, the costs for Poland ranged from 136, through 174 to 185 million euros for WARM, BASE AND COLD years, respectively. As in the health impact assessment, it is not possible to evaluate the economic impact for the entire country based on the measurement network. The calculations indicate that the 5 most populated cities in Poland have the highest economic losses, exceeding 5 million euros each. In the BASE and COLD year, the values are similar between each other (5% higher costs in 2010 compared to 2018), while in 2020 they are about 22% lower than in 2018. In the case of the measurements data, health costs are significantly higher. The largest values are for Krakow and range from €9 million in 2020 to €19 million in 2010 and are on average 2 times higher compared to Warsaw. Katowice also stands out from other cities, with higher economic costs in the COLD year than in the capital city.

4. Discussion

The evaluation of EMEP4PL shows that the model has a general tendency to underestimate measured BaP concentrations in Poland with NMB equal to −0.52 and NMGE equal to 0.62. Despite this, the time series of the modelled and observed BaP values indicate that the model correctly reproduces the temporal variability of the BaP concentrations throughout the year, and the precision of the model is similar to the results for PM_{10} concentrations. Werner et al. (2018) compared modelled with EMEP4PL and observed PM_{10} concentrations for Poland for the full year 2015. Their results have shown underestimation of measured concentrations with annual mean NMB for PM_{10} equal to −0.45 and NMGE equal to 0.58. The lowest model error was during the winter period which is the same as for BaP results. The underestimation of measured particulate matters by chemical transport models has been previously reported by (e.g. Im et al., 2015; Lin et al., 2017). Differences between modelled and measured concentrations touch on a much broader discussion of the station's representativeness and modelling accuracy, which has been frequently addressed in the literature (e.g.

Table 3
Number of cases of lung cancer per year caused by BaP concentrations.

Data	Population	COLD	BASE	WARM	Measurements	Measurements	Measurements
Year		2010	2018	2020	2010	2018	2020
		Number of lung cancers per year					
Poland*	37 972 812	76.9	72.6	56.6	–	–	–
Warszawa	1 792 718	6.2	6.1	4.3	2.3	3.2	3.2
Krakow	780 796	3.4	3.3	2.9	**7.9**	**5.1**	**3.8**
Lodz	667 923	2.1	2.1	1.6	5.6	3.5	2.3
Wroclaw	641 201	2.3	2.1	1.7	3.4	2.2	2.0
Poznan	530 464	1.7	1.5	1.2	0.0	1.9	1.3
Gdansk	470 633	1.1	1.1	0.8	2.2	1.2	0.5
Szczecin	398 472	0.6	0.6	0.4	1.2	1.2	0.5
Bydgoszcz	341 692	0.9	0.9	0.6	1.7	1.9	1.0
Lublin	337 788	0.9	0.9	0.8	0.0	0.8	0.8
Bialystok	296 401	1.1	1.1	0.9	0.0	0.5	0.6
Katowice	289 162	**1.2**	**1.2**	**0.9**	**2.9**	**1.7**	**1.3**
Gdynia	244 104	0.5	0.5	0.4	0.6	0.0	0.0
Czestochowa	215 905	0.7	0.8	0.6	1.0	0.8	0.7
Radom	208 091	0.8	0.7	0.6	1.1	0.7	0.6

* Calculations for Poland are based on average concentrations from the entire country area.

Table 4
Economic costs of lung cancer due to BaP concentrations in Poland.

Data	Population	COLD	BASE	WARM	Measurements	Measurements	Measurements
Year		2010	2018	2020	2010	2018	2020
		Value adjusted for latency (€M)					
Poland*	37 972 812	**184.5**	**174.2**	**135.8**	–	–	–
Warszawa	1 792 718	14.8	14.7	10.3	5.5	7.7	7.7
Krakow	780 796	8.2	7.9	6.9	**19.0**	**12.3**	**9.0**
Lodz	667 923	5.0	4.9	3.9	13.5	8.4	5.5
Wroclaw	641 201	5.6	5.1	4.1	8.2	5.3	4.7
Poznan	530 464	4.0	3.7	2.8	–	4.6	3.2
Gdansk	470 633	2.6	2.7	1.9	5.3	2.9	1.1
Szczecin	398 472	1.5	1.4	1.0	2.8	3.0	1.1
Bydgoszcz	341 692	2.2	2.2	1.6	4.1	4.5	2.5
Lublin	337 788	2.3	2.3	1.9	–	2.0	2.0
Bialystok	296 401	2.6	2.7	2.1	–	1.3	1.4
Katowice	289 162	**2.8**	**2.9**	**2.2**	**7.0**	**4.1**	**3.0**
Gdynia	244 104	1.2	1.2	0.9	1.4	–	–
Czestochowa	215 905	1.8	1.8	1.5	2.4	1.9	1.6
Radom	208 091	1.8	1.7	1.3	2.7	1.7	1.5

* Calculations for Poland are based on average concentrations from the entire country area.

Duyzer et al., 2015; Santiago et al., 2013; Vitali et al., 2016; Piersanti et al., 2015; Craig et al., 2020). For instance, one of the factors of the accuracy of the modelling is the uncertainty of emissions data. For the Polish inventory, possible errors are mainly related to fuel data, which are based on certain assumptions described in detail (Gawuc et al., 2021). Atmospheric BaP concentrations might be associated with waste burning, which is illegal and, as such, unreported and not directly included in the IEP-NRI inventory. The issue is, however, addressed by a relatively high BaP emission factor (see Table 2 in Gawuc et al. 2021). Moreover, customs, ecological awareness, and wealth inequalities among Polish citizens generate an additional uncertainty and inconsistency in terms of BaP spatial patterns. A major challenge is to distinguish emission sources from individual stoves with buildings connected to district heating networks.

We modelled BaP in the atmosphere as non-reactive particles, which might be another source of uncertainties. It is known that particulated BaP can be degraded by ozone (San José et al., 2013), however the impact of this process on the modelling results over Poland is limited due to clearly predominant emissions and high concentrations during the cool season. A similar approach for modelling BaP concentrations with CAMx over the Czech Republic has previously been used by Schreiberová et al. (2020).

The spatial and temporal distribution of BaP emissions and concentrations in Poland is closely related to pollutant emissions from the residential sector. About 90% of PAH emissions in Poland are related to household emissions (Bebkiewicz et al., 2021). It is similar to other European countries as residential, commercial and industrial combustion are by far the most important BaP emission sectors, contributing 87% of the estimated total BaP emissions in the EU (EEA, 2021). Compared to other European countries, Poland, has the highest average BaP emissions per capita from the residential sector (Schreiberová et al., 2020). The main reason for that is high coal and wood consumption and old types of boilers. Anti-smog resolutions have been introduced in 14 of Poland's 16 voivodeships to protect and improve air quality. The aim of the introduced regulations is to use only heating devices that meet high standards for emissions, and to ban the use of the worst-quality coal fuels and damp biomass, however, due to the current (2022) problems with access to gas, a return to the mass burning of low quality fuels in the residential sector is observed.

Despite the model underestimating BaP concentration, the results for the BASE and COLD year show that about 98% of the Polish population is exposed to BaP concentrations above the target annual level of 1 ng m^{-3}. For the WARM year it is 90% of the population. The exceedances of BaP TV concentrations for Poland are much higher compared to average values for Europe. Guerreiro et al., 2016 estimated that 20% of the European population is exposed to BaP background ambient concentrations above the EU TV. Their calculations have shown that the average population-weighted concentration of BaP in Europe was about 0.9 ng m^{-3} in 2012. Despite the reduction in coal and wood burning for heating in Europe, concentrations above 1.0 ng m^{-3} were recorded in

27% of the monitoring stations reported, most of which were urban (79%) or suburban (15%) (EEA, 2022).

The modelling results enable estimation of the health effects for the entire country. It is not possible with results from in-situ measuring stations, since they do not fully cover the entire country. However, such a comparison is applicable for individual cities, because the modelling result is compared in the grid cell where the measurement station is located. The total number of lung cancers per year due to BaP exposure based on modelled data in Poland is 73, 77 and 57 for the BASE, COLD and WARM year, respectively with about 8% of all cases recorded in Warszawa and another 5% in Krakow. Guerreiro et al. (2016) have estimated that the number of lung cancers within the modelled domain, covering about 60% of the countries reporting to EEA is equal to 370, with the largest health impact in the central-eastern European countries. It should be noted that other health endpoints such as reduced infant weight at birth, increased incidence of skin and bladder cancer, effects on children's cognitive development and ADHD behaviour problems, or fatal ischemic heart disease, are not included in the health analysis tools. Other studies also emphasize that BaP intake via deposition and uptake in the food chain could play a more important role in some regions (Bukowska et al., 2022; Sampaio et al., 2021).

The risk factor for BaP exposure to outdoor air pollution was assumed only. Uncertainties in the use of the response function from WHO (1987, 2000) are recognised. In particular, its use requires extrapolation from the high concentration to which coke-oven workers are exposed to lower ambient levels. Other risk factors, such as smoking or indoor ambient air, were not considered. Comparison of our results with those of the other studies shows that the effect of smoking on the number of lung cancer cases is much greater than outdoor BaP concentrations. According to the WHO, smoking (first hand and second hand) causes 87% of all lung cancer cases among men and 71% of cases among women in Poland (WHO, 2019). In 2019, 22 003 new cases of lung cancer were reported in Poland (Polish National Cancer Registry). This data indicates that the number of lung cancer cases due to smoking (active and passive) annually in Poland is more than 15 000. Compared to lung cancer associated with BaP concentrations, the number of cases related to smoking is more than 200 times higher in the BASE year.

Lung cancer latency period of 13.6 years was assumed based on data from the EEA report (Schucht et al., 2020). Also, when studying the estimation of the length of time between the biological initiation of cancer and diagnosis by developing a Weibull-type survival model, the exact period for lung cancer is indicated as 13.6 years. Furthermore, statistical analysis showed an identical exact and modelled lung cancer latency period (Nadler and Zurbenko, 2014). Assuming in the study that exposure to BaP from outdoor air pollution affects the entire population, a reference value was used. However, the latency period for lung cancer among workers in many industries including coal gas production, aluminum smelting and others is assumed to be shorter and can be 10 years (eg. Brown et al., 2012).

It is indicated that exposure to PM2.5 is associated with a significant percentage of lung cancer deaths (23.9%). In addition, it is recognized that lung cancer is one of the most significant causes of cancer-related mortality due to PM25 exposure, and non-small cell lung cancer (NSCLC) accounts for 80% of lung cancer deaths. However, study result shows that exposure to BaP significantly increases the risk of non-small cell lung cancer (NSCLC), the most common type of lung cancer, by inhibiting the expression of ring finger protein 182 (Y. Liu et al., 2023). In addition, BaP induces gene mutations thereby playing a carcinogenic role in many cancers (Chen et al., 2017). As a result of the fact that BaP concentrations in outdoor air are collinearly related to PM concentrations, there is uncertainty in the obtained results of the cancer case. Nonetheless, the assumptions made about the unit risk factor for BaP inhalation being set at 8.7×10^{-2} lung cancers per 1 μg m^{-3} to some extent reduces this ambiguity.

5. Summary and conclusions

This paper presents the first application of the EMEP/MSC-W model for BaP modelling. The model was run for Central Europe, Poland, which is characterised by the highest concentrations of BaP in Europe. The evaluation of the model is presented for 2018, which is defined as the BASE year, and compared with 7-days average BaP concentrations from 120 observational stations. To evaluate the impact of meteorological conditions on BaP concentrations, the warm year (2020) and the cold year (2010) were selected from 2010 to 2020 years and were defined as WARM and COLD run (emissions were kept constant between years for these runs at the level in 2018). The three model runs (BASE, WARM and COLD) were used to analyse the impact of BaP particles on population health and economic costs for the entire Poland and the largest cities. The results show that:

- Despite the model underestimating measured BaP concentrations (NMB equal to − 0.52) the annual EU TV of 1 ng m^{-3} is exceeded for 85% of Poland's for the BASE year. The time series of BaP concentrations shows that the temporal variability of BaP concentrations is properly represented by the model. The highest concentrations occur from December to March and exceed 4 ng m^{-3} for the COLD year and 2 ng m^{-3} for the WARM year. The highest values are recorded in southern Poland (Upper Silesia industrial and highly urbanized region) and in the largest cities and are closely related to emissions from the residential sector. BaP concentrations in the summer months are about 30 times lower than in the winter of the COLD year and 20 times lower for the WARM year.
- The annual EU TV of 1 ng m^{-3} is exceeded for 91% of Poland's area in 2010 and for 64% of the area in 2020, indicating a significant influence of meteorological conditions on BaP concentrations in Poland. In most of the area, BaP concentrations in the COLD year are at least 20 % higher than in the WARM year, while for western Poland they are even more than 50% as high in 2010 compared to 2020.
- -The results show that for each run above 90% of the Polish population is exposed to BaP concentrations above the annual TV of 1 ng m^{-3}, more than 50% of the population is exposed to a value at least twice as high. High BaP concentrations have serious health implications and the number of lung cancers in Poland due to BaP exposure varies from 57 to 77 cases for the WARM and COLD year, respectively. The variation in lung cancer incidence is reflected in the economic costs which ranged from 136, through 174 to 185 million euros for WARM, BASE and COLD model runs, respectively. Note that the results presented do not include other sources leading to human exposure to BaP (e.g. grilling or broiling foods, cigarette smoke). The analysis also does not indicate other health effects such as the incidence of liver and other organ cancers or reduced fertility, so the impact is certainly greater.
- The highest BaP concentrations are in areas with the largest share of the municipal and residential sectors. It is caused by the fact that due to financial reasons and low community awareness, households often use poor-quality solid fuels, burn waste, prohibited types of coal (e.g., lignite, coal fines) and other prohibited fuels (e.g., used motor oil). This is also probably one of the reasons for the model – measurements mismatch as fuel composition is not accurately known. As expected, meteorological conditions have a significant impact on the distribution of BaP concentrations and the highest concentrations occur during the anomalously cold heating period. Our results confirm the scale of the large BaP issues in Central Europe, as indicated previously by (e.g. Schreiberová et al., 2020; Widziewicz et al., 2017). With the energy crisis and the return to burning low quality fossil fuels in households for economic reasons, the problem is not going to be solved any time soon despite the corrective steps taken earlier.

CRediT authorship contribution statement

Paweł Porwisiak: Conceptualization, Software, Writing – original draft, Writing – review & editing, Visualization. **Małgorzata Werner:** Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing, Supervision. **Maciej Kryza:** Methodology, Software. **Massimo Vieno:** Methodology, Software. **Mike Holland:** Methodology, Writing – original draft, Writing – review & editing. **Helen ApSimon:** Conceptualization, Writing – original draft. **Anetta Drzeniecka-Osiadacz:** Methodology, Validation. **Krzysztof Skotak:** Resources. **Lech Gawuc:** Writing – original draft, Resources. **Karol Szymankiewicz:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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