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AIR POLLUTION IN ŁÓDŹ IN 2018–2024: EMISSIONS, METEOROLOGICAL CONDITIONS AND THE HEIGHT STRUCTURE OF URBAN DEVELOPMENT

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A b s t r a c t

Mean annual concentrations of five air pollutants – benzo(a)pyrene (BaP), benzene (C_6H_6), NO_2, PM_{10} and $PM_{2.5}$ – were examined in Łódź in 2018–2024 together with reported emissions, meteorological conditions and the structure and intensity of the city's development, the latter analysed for 97,517 buildings in 36 auxiliary units. Spearman rank correlation with Benjamini–Hochberg correction was applied. In 2024 the concentrations of all five pollutants were lower than in 2018, most markedly for BaP (−58.2%) and NO_2 (−43.0%). This documents a decrease between these years; no trend over the whole period was significant after correction. Emission–concentration relationships were significant for NO_2 ($\rho = 0.96$) and BaP ($\rho = 0.89$), whereas no meteorological one was. The share of low-rise buildings falls from 90.86% of their number to 48.51% of the pseudo-usable floor area, and intensity ranges from 13,062 m^2/ha in Katedralna to 176 m^2/ha in Łagiewniki.

Keywords: air pollution, building structure, particulate matter, urban form, urban ventilation

1. INTRODUCTION

The physical form of a city is one of the factors that determine the concentrations of air pollutants measured within it. Compact development increases the roughness of the underlying surface, weakens airflow and limits the exchange of air between the city and its surroundings, while at the same time modifying the radiation balance. Progressive urbanisation may therefore lead to elevated pollutant concentrations, particularly during periods of unfavourable meteorological conditions [1-3].

Emissions within a city depend mainly on the number of inhabitants and on the magnitude of industrial and transport-related sources [4-7]. Concrete and asphalt surfaces, whose albedo is low, accumulate heat; together with vehicle traffic, greenhouse gas emissions and building heating, this leads to the formation of an urban heat island. The resulting temperature contrast between the city and its

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surroundings produces a local low-pressure system that draws air inwards from the outskirts, hampering the removal of pollutants and favouring their accumulation [8, 9].

The problem of designing urban ventilation has been the subject of research since the nineteenth century. It has gained particular importance in view of the strong anthropogenic transformation of the environment, manifested in increased emissions, soil sealing and the expansion of built-up areas. A growing urban population contributes to the degradation of the urban fabric and to uncontrolled development, and thus to the modification of climatic elements such as sunshine duration, temperature, humidity and wind speed. The resulting phenomena – the urban heat island and the reduced exchange of air and of the pollutants it contains – directly affect the quality of life and the health of inhabitants, so that ensuring appropriate climatic conditions within cities becomes a necessary component of sustainable urban development [10-13].

As a result of the considerable roughness of the urban surface, wind speed is markedly reduced: on average by 30% in the city centre and by 15–20% in outlying housing estates. Winds of 4–5 m/s are weakened while weak winds are accelerated as they are channelled between buildings, and the frequency of calm conditions increases; the dynamic interaction between buildings and airflow also causes strong deflection of wind direction. The modification of the wind field above the city additionally results from the pressure difference between the city and its surroundings, which is related to the heat surplus in the city. Under conditions of weak atmospheric circulation an urban heat island develops, together with an associated system of breeze-type winds directed towards the city interior. Transport corridors and valley floors running from the extra-urban zone towards the centre allow air from outside to penetrate the city, and appropriately planned ventilation corridors with low surface roughness and a high proportion of greenery make it possible to exploit the urban breeze [14, 15].

Exposure to air pollution is among the best-documented environmental health hazards. Epidemiological studies confirm that it contributes to diseases of the respiratory system (asthma, lung cancer, exacerbations of COPD, respiratory tract infections), the circulatory system (myocardial infarction, arterial hypertension, ischaemic heart disease, arrhythmias, heart failure) and the nervous system (stroke, impaired memory and concentration, accelerated ageing of the nervous system), as well as to cancers and complications of pregnancy [16-21]. A substantial proportion of the global deaths attributed to air pollution is associated with the combustion of fossil fuels [22].

The dispersion of pollutants also depends on meteorological conditions and relief [23]. Wind speed determines the rate of transport and wind direction the direction of displacement; under weak winds concentrations increase, whereas thermal inversions limit vertical transport and retain pollutants in the near-surface layer of the atmosphere. The season is likewise relevant: in winter, low temperatures increase emissions from the municipal and residential sector, whereas in summer high temperatures and strong insolation favour the formation of secondary pollutants [23-25]. Urban greenery and blue-green infrastructure may counteract these phenomena, although their effectiveness depends on the local spatial layout and on whether planning takes development and ventilation into account [26].

Although the influence of urban structure on air quality has been well described in qualitative terms, the quantitative relationships between the intensity and height of development and mean annual pollutant concentrations in Polish cities remain insufficiently documented, particularly when the magnitude of emissions and meteorological conditions are considered simultaneously [27]. Combining concentration measurements from the State Environmental Monitoring network, emission reporting to KOBiZE and the spatial building database BDOT10k makes it possible to describe both dimensions for a single city within one coherent framework, and to establish how far the available data allow their relationship to be assessed.

The aim of this study is twofold: to determine the variation in mean annual concentrations of selected air pollutants in Łódź in the period from 2018 to 2024, taking into account reported pollutant

emissions and selected meteorological conditions, and to characterise the structure and intensity of urban development in the city as the spatial context of those concentrations. No direct quantitative analysis of the relationship between the intensity and height of development and pollutant concentrations was performed; the building characteristics constitute the spatial context of the air-quality analysis. This results from the different spatial resolution of the data and from the lack of linkage between the building indicators and the locations of the monitoring stations. The research gap identified above is therefore recognised, but not fully filled, by the present study.

2. MATERIAL AND METHODS

2.1 Study area

Łódź is located in central Poland, on the boundary between the Łask Plateau, to which its western part belongs, and the Łódź Hills in its eastern part. The city is characterised by a concentric structure, both in terms of the intensity of development and in terms of building height. The central part of Łódź consists of an area of compact development containing numerous historic architectural objects dating back to the nineteenth century. These districts are surrounded by newer, post-war industrial areas, housing estates and recreational areas. From the 1990s onwards, distinct urban and functional transformations have taken place in the central districts, the most characteristic manifestation of which is the revitalisation of nineteenth-century industrial complexes and their conversion to residential, office and commercial-recreational functions. The industry of Łódź has likewise undergone substantial change.

The ventilation system of Łódź results from local physiographic conditions, the urban layout, the climatic features of the region and phenomena associated with the functioning of the city. These factors may either support airflow within the city or, conversely, constitute an aeration barrier and thereby contribute to a deterioration in the quality of life of the inhabitants. The first of these features – the specific relief resulting from the city's position between the Polish Uplands and the Polish Lowlands, that is, the inclination from the north-east towards the south-west, together with the presence of the Łódź Hills – inhibits the inflow of air into the city [28, 29].

The basic indicators characterising Łódź are summarised in Table 1.

Table 1. Basic indicators of Łódź

Indicator	Łódź
Area [km^2]	293
Share of the country's area [%]	0.094
Green areas [km^2]	14
Forests [km^2]	9
Built-up areas [%]	44
Population density [inhab./km^2]	2292

Source: Statistics Poland (GUS), 2025.

2.2 Concentration, emission and meteorological variables

The analysis covered annual pollutant concentrations and their relationships with reported emissions and meteorological conditions in Łódź in the years 2018–2024. All analyses were carried out at the level of calendar years. Five pollutants were examined: BaP (benzo[a]pyrene), C_6H_6 (benzene), NO_2, PM_{10} and $PM_{2.5}$; seven annual values were available for each of them.

Concentrations were measured at urban background monitoring stations of the State Environmental Monitoring network operated by the Chief Inspectorate of Environmental Protection [30]: in Łódź, ul. Gdańska and al. Jana Pawła II (φ 51.754613°, λ 19.434920°). Annual concentrations

were calculated as the mean of 12 monthly values. Point measurements at two stations do not capture the full spatial variability of concentrations within the city; the series are therefore treated as indicators of the year-to-year change in concentration levels, not as a spatial mean for Łódź. Emissions reported to the National Centre for Emissions Management (KOBiZE) were analysed for five categories corresponding to the measured concentrations; SO_x/SO_2 was considered only descriptively because no corresponding concentration series was available. The meteorological variables – mean air temperature, mean wind speed and total precipitation – were obtained for the years 2018–2024 from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB).

Emissions were expressed in kg per km^2 of city area per year. The emission–concentration and meteorology–concentration relationships, as well as trends over time, were assessed using Spearman rank correlation. Two-sided p-values were determined exactly, taking into account all possible orderings of the seven years.

The p-values were corrected using the Benjamini–Hochberg (BH) procedure separately within each family of tests presented: emission–concentration (5 tests), meteorology–concentration (15 tests) and concentration trends (5 tests). Corrected values are denoted pBH, and $pBH < 0.05$ was treated as statistically significant. Because only seven years were available, no models including the year and the three meteorological variables simultaneously were fitted. The stability of the significant emission–concentration correlations was checked in three ways: by omitting each year in turn, by the partial Spearman correlation controlling for year, and by the Spearman correlation between year-to-year changes in emission and concentration ($n = 6$, exact two-sided p-value).

2.3 Building structure and intensity

A detailed analysis of the building height structure was conducted using data from the Polish Database of Topographic Objects (BDOT10k) [31]. The analysis covered 97,517 buildings located within the boundaries of Łódź's 36 auxiliary units. The building geometries, footprint areas and the LICZ_KONDY attribute, which specifies the number of above-ground storeys, were used.

The buildings were assigned to four height classes: low-rise (N) – up to and including 4 above-ground storeys; medium-rise (SW) – from 5 to 9 above-ground storeys; high-rise (W) – from 10 to 18 above-ground storeys; and very high-rise (WW) – more than 18 above-ground storeys. The adopted ranges correspond to the storey-number criteria included in the classification established by the Regulation of the Minister of Development and Technology on the technical requirements to be met by buildings and their location [32]. Owing to the absence of a consistent building-height attribute, the classification was operationally based on the number of storeys.

For buildings for which the number of storeys recorded in BDOT10k was zero, a minimum value of one storey was assumed. This prevented buildings with a non-zero footprint area from contributing no value to the building-intensity indicator.

The building structure was assessed using three measures: the number of buildings, the building footprint area and the pseudo-usable floor area. The latter was calculated as the product of the building footprint area and the number of storeys, and was treated as an approximate measure of the vertical intensity of development rather than as the actual usable floor area defined under formal measurement standards. The results were aggregated for the entire city and for each auxiliary unit.

3. RESULTS

3.1 Concentration trends

In 2024 the concentrations of all five pollutants were lower than in 2018 (Table 2). A comparison of two years alone does not, however, determine whether the change was monotonic throughout the period.

None of the five monotonic concentration trends was significant after Benjamini–Hochberg correction. The smallest corrected p-values were recorded for BaP ($\rho = -0.89$; $p = 0.0123$; pBH = 0.0595) and PM_{10} ($\rho = -0.86$; $p = 0.0238$; pBH = 0.0595) (Table 2, Fig. 1).

Table 2. Annual pollutant concentrations in Łódź in 2018 and 2024 and Spearman trend statistics for 2018–2024

Pollutant	Unit	2018	2024	Change 2018–2024 [%]	ρ (trend)	p	pBH
BaP	ng/m^3	4.54	1.90	−58.2	−0.89	0.0123	0.0595
C_6H_6	µg/m^3	1.39	1.13	−19.2	−0.43	0.3536	0.3536
NO_2	µg/m^3	24.0	13.7	−43.0	−0.71	0.0881	0.1369
PM_{10}	µg/m^3	37.8	30.5	−19.2	−0.86	0.0238	0.0595
$PM_{2.5}$	µg/m^3	21.3	16.2	−23.7	−0.68	0.1095	0.1369

Source: own elaboration on the basis of data of the Chief Inspectorate of Environmental Protection (GIOŚ). BaP is given in ng/m^3, the remaining pollutants in µg/m^3; percentages were calculated from unrounded values. ρ – Spearman rank correlation between concentration and year (n = 7); p – exact two-sided p-value; pBH – p-value adjusted by the Benjamini–Hochberg procedure across the five trends.

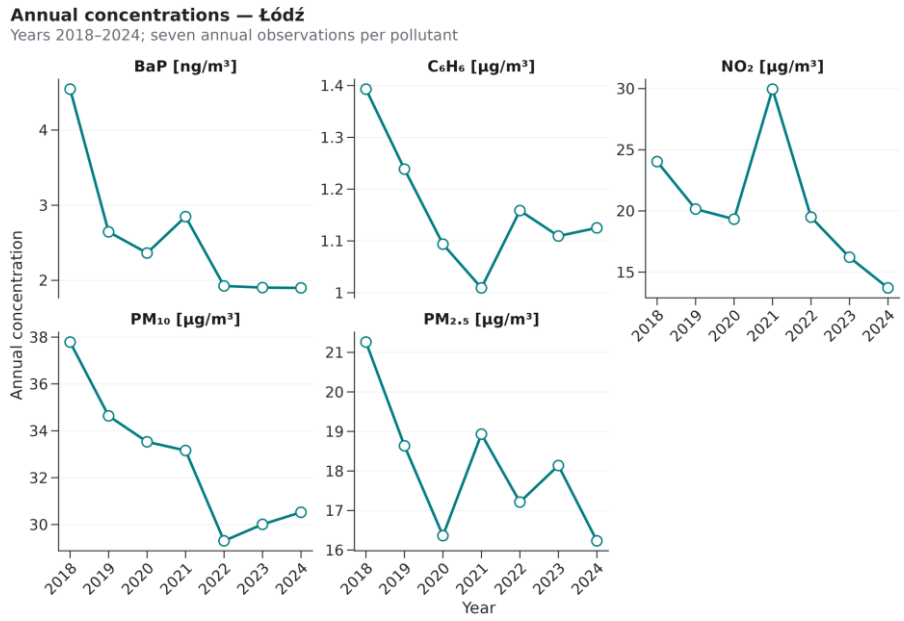


Fig. 1. Annual concentrations of five pollutants in Łódź from 2018 to 2024. Each panel contains seven annual values; the unit is stated in the panel heading. Source: own elaboration based on data of the Chief Inspectorate of Environmental Protection (GIOŚ)

3.2 Emissions and concentrations

After Benjamini–Hochberg correction, significant positive emission–concentration relationships were found for NO_2 ($\rho = 0.96$; $p = 0.0028$; pBH = 0.0139) and BaP ($\rho = 0.89$; $p = 0.0123$; pBH = 0.0308). Years with higher reported emissions therefore tended to be years with higher concentrations of these pollutants (Figs. 2 and 3).

For PM_{10} the correlation between reported emission and concentration was also positive ($\rho = 0.79$), but it did not reach significance after correction.

Because both the emission and the concentration series decreased over the period, the stability of the two significant associations was examined further. With single years omitted in turn, ρ ranged from 0.94 to 1.00 for NO_2 and from 0.83 to 1.00 for BaP. For NO_2 the association remained positive after the common trend was taken into account (partial Spearman correlation controlling for year: 0.93), but this rests mainly on the simultaneous maximum of both series in 2021 – without that year reported NO_x/NO_2 emissions decreased in every year; the correlation between year-to-year changes in emission and concentration was 0.83 and was not significant ($n = 6$; $p = 0.0583$). For BaP, reported emissions decreased in every year (ρ with year = −1.00), so the effect of emissions cannot be separated from the trend; the correlation between year-to-year changes was 0.66 ($p = 0.1750$). Neither association can therefore be distinguished from the common downward course of both series with confidence.

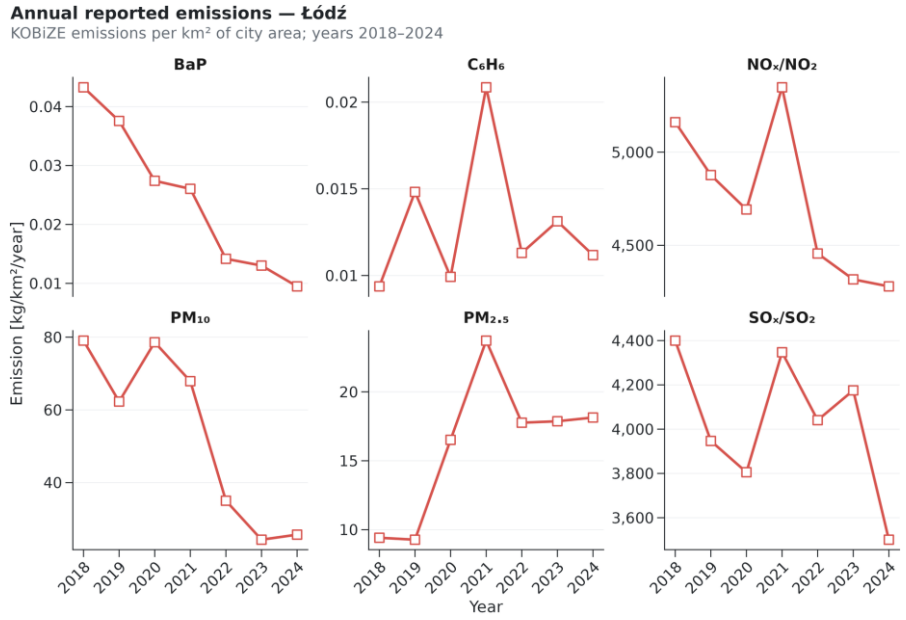


Fig. 2. Annual emissions reported to KOBiZE in Łódź from 2018 to 2024, expressed per km^2 of city area. Six emission categories are shown. No corresponding concentration series was available for SO_x/SO_2. Source: own elaboration based on data of the National Centre for Emissions Management (KOBiZE)

BaP emissions decreased throughout the period. NO_x/NO_2 and PM_{10} emissions fell markedly in 2022–2024 after earlier increases, whereas $PM_{2.5}$ emissions remained above the 2018 level after peaking in 2021. C_6H_6 and SO_x/SO_2 fluctuated irregularly.

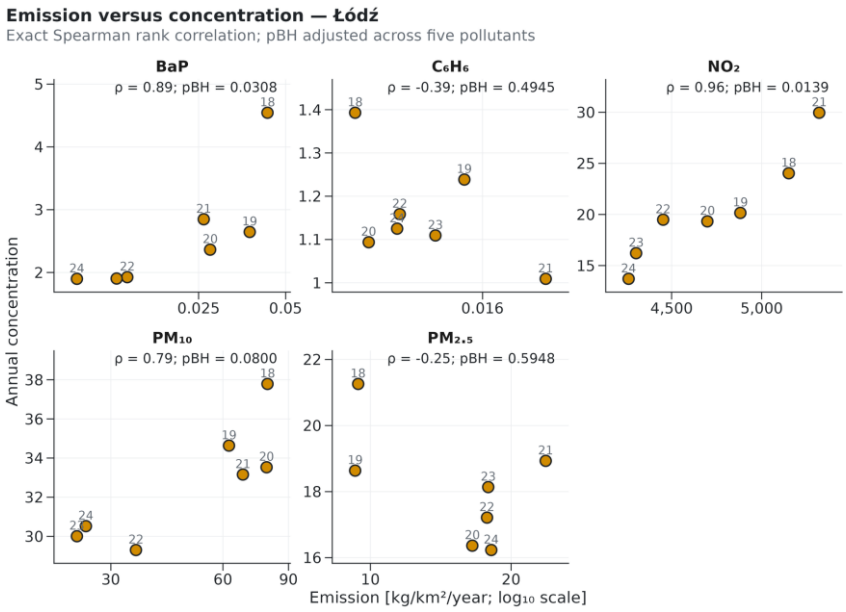


Fig. 3. Association between emissions reported to KOBiZE and annual concentration in Łódź. Point labels give the last two digits of the year. The coefficient ρ is the Spearman rank correlation across seven years. P values were adjusted by the Benjamini–Hochberg method across five pollutants; the figure reports pBH. The correlations were not adjusted for temporal trend. Source: own elaboration based on GIOŚ and KOBiZE data

3.3 Meteorological conditions

None of the 15 meteorology–concentration tests was significant after Benjamini–Hochberg correction. The largest absolute correlation was recorded for the precipitation total–C_6H_6 pair ($\rho = -0.82$; $p = 0.0341$; pBH = 0.5119) (Figs. 4–6).

A weaker negative correlation linked air temperature with NO_2.

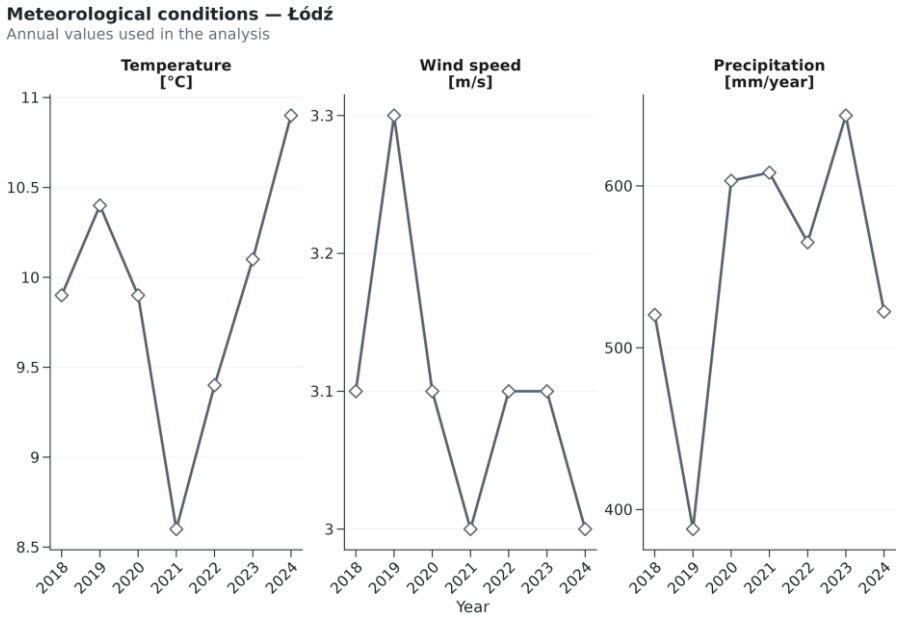


Fig. 4. Annual temperature, wind speed, and precipitation values used in the analysis for Łódź, 2018–2024. Source: own elaboration based on data of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)

Temperature reached a minimum in 2021 and a maximum in 2024. The annual wind speed varied little and remained within the range of 3.0–3.3 m/s, whereas precipitation fluctuated strongly between years, with a minimum in 2019 and a maximum in 2023.

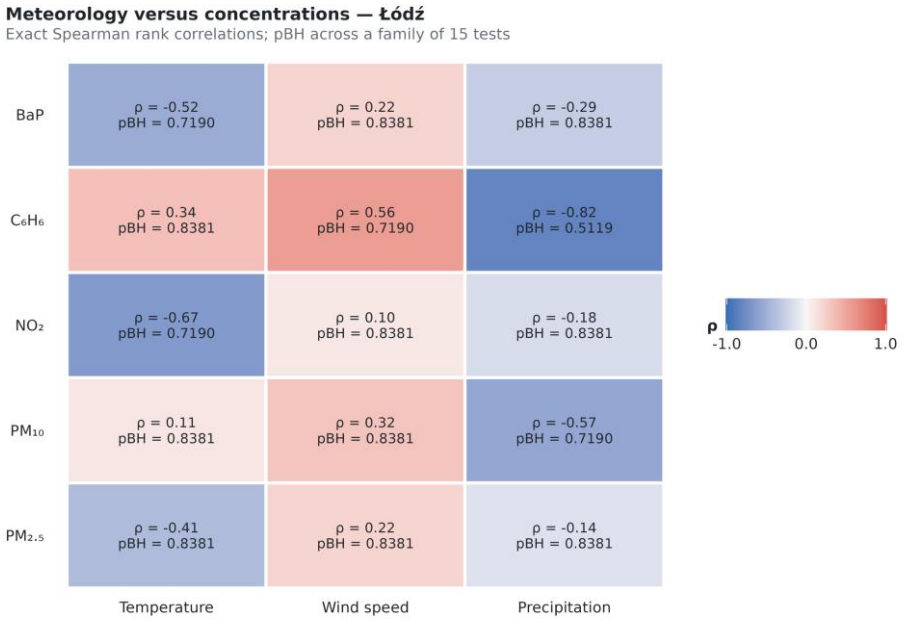


Fig. 5. Spearman rank correlations between three meteorological variables and concentrations of five pollutants in Łódź. Each correlation is based on seven annual observations. P values were adjusted jointly across 15 tests; cells report pBH. Source: own elaboration

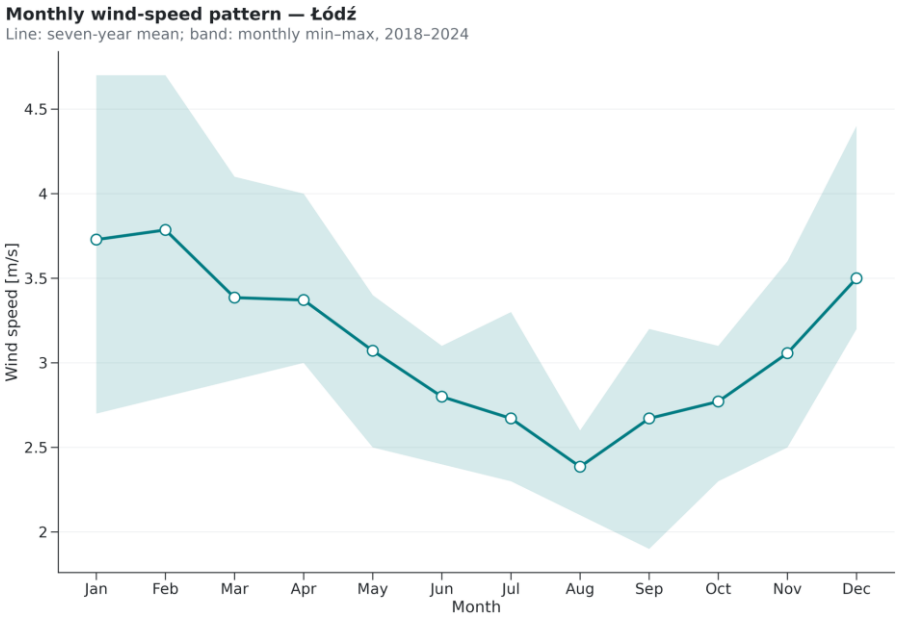


Fig. 6. Monthly wind-speed pattern in Łódź. The line gives the seven-year mean for each month; the band gives the minimum and maximum across those years for that month. Source: own elaboration

Wind speed was highest in February, decreased until August and then increased again. The greatest between-year variability occurred in winter, particularly in January and February.

3.4 Building structure and intensity

Łódź is characterised by a large proportion of low-rise buildings. Class N accounts for 90.86% of all buildings and 77.78% of the total building footprint area. When the number of storeys is taken into account, however, its share decreases to 48.51% of the pseudo-usable floor area. Medium-rise buildings account for 38.98%, high-rise buildings for 11.99% and very high-rise buildings for 0.51% of this indicator. The shares of the four height classes are summarised in Table 3.

The results confirm the predominance of a relatively low-rise building structure in Łódź while also demonstrating the substantial contribution of medium-rise development in the central and selected residential parts of the city. The share of this class increases from 8.22% of the total number of buildings to almost 39% of the pseudo-usable floor area.

The largest total pseudo-usable floor area was recorded in the Katedralna unit, which accounts for 8.12% of the citywide value. It is followed by Stare Polesie (7.59%), Chojny-Dąbrowa (5.32%), Stary Widzew (5.25%) and Bałuty-Centrum (5.19%). The concentration of high values in Katedralna and Stare Polesie reflects the compact, multi-storey urban fabric of the city centre.

The largest combined shares of classes W and WW were recorded in Widzew-Wschód (46.16%), Karolew-Retkinia Wschód (42.25%) and Piastów-Kurak (31.99%) – areas in which multi-storey residential complexes constitute a substantial part of the building structure. The largest shares of class SW were recorded in the Józef Montwiłł-Mirecki Housing Estate (92.28%), Katedralna (65.92%), Stare Polesie (65.34%), Koziny (61.36%) and Śródmieście-Wschód (60.35%). The exceptionally high value recorded for the Józef Montwiłł-Mirecki Housing Estate should be interpreted with caution because of its small area and the limited number of buildings analysed. Very high-rise buildings were identified only in the Katedralna and Stoki-Sikawa-Podgórze units.

The highest building intensity was recorded in the Katedralna unit, where the pseudo-usable floor area amounts to 13,062 m^2/ha, corresponding to a simplified floor area ratio of approximately 1.31. It is followed by Stare Polesie (7,575 m^2/ha), Śródmieście-Wschód (7,342 m^2/ha), Górniak (6,259 m^2/ha) and Stary Widzew (5,201 m^2/ha). High values were also recorded in Karolew-Retkinia Wschód (5,186 m^2/ha) and Piastów-Kurak (4,940 m^2/ha), owing to the substantial proportion of multi-storey residential development. The lowest building intensity was recorded in Łagiewniki (176 m^2/ha), Wzniesień Łódzkich (211 m^2/ha), Mileszki (269 m^2/ha) and Nad Nerem (361 m^2/ha). These results confirm the strong contrast between the compact urban fabric of the city centre and multi-family housing estates on the one hand, and the sparsely developed peripheral areas on the other. The spatial distribution of the indicator is shown in Fig. 7, and the detailed results for individual auxiliary units in Table 4.

Table 3. Shares of building height classes in the pseudo-usable floor area of Łódź

City	N [%]	SW [%]	W [%]	WW [%]
Łódź	48.51	38.98	11.99	0.51

Source: own elaboration on the basis of BDOT10k data. N – low-rise, SW – medium-rise, W – high-rise, WW – very high-rise buildings

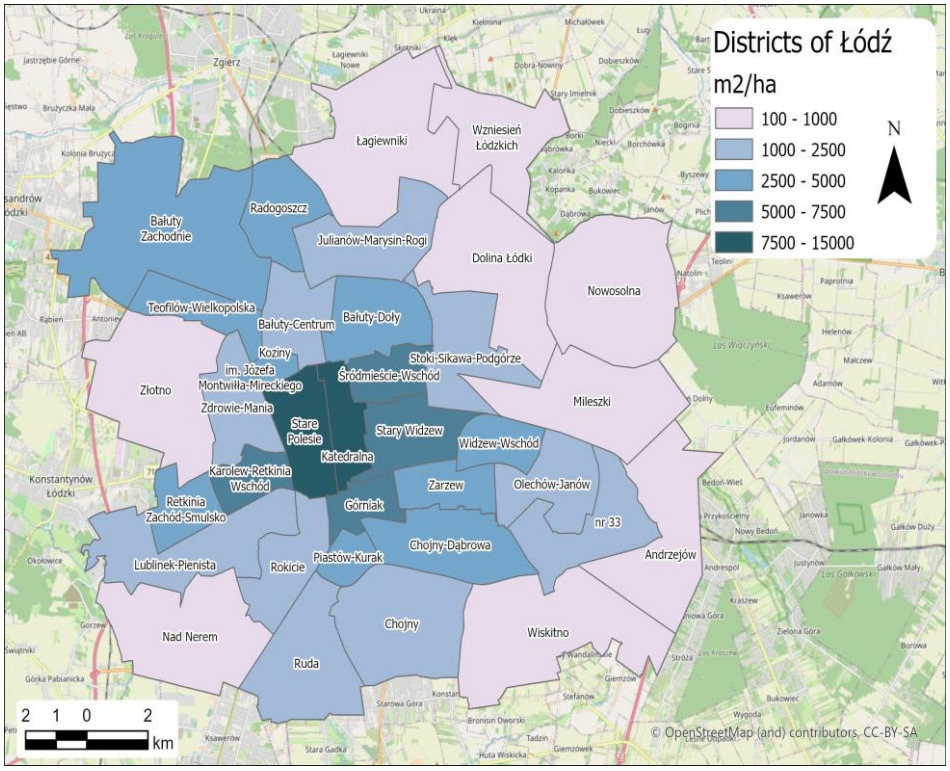


Fig. 7. Spatial differentiation of the pseudo-usable floor area of buildings per 1 ha of the auxiliary unit area in Łódź. The indicator was calculated as the quotient of the sum of the building footprint area multiplied by the number of storeys and the area of the auxiliary unit. Source: own elaboration based on BDOT10k; map base: OpenStreetMap

Table 4. Building structure and intensity by auxiliary unit in Łódź

Auxiliary unit	Area [ha]	Pseudo-usable floor area [m²/ha]	N [%]	SW [%]	W [%]	WW [%]	Dominant class
Andrzejów	1,197.00	511.23	100.00	0.00	0.00	0.00	N
Bałuty-Centrum	2,154.49	1,409.17	29.63	45.45	24.92	0.00	SW
Bałuty-Doły	523.33	4,722.07	26.91	59.92	13.17	0.00	SW
Bałuty Zachodnie	672.63	4,513.59	88.77	9.77	1.47	0.00	N
Chojny	1,203.84	2,200.23	53.62	41.18	5.20	0.00	N
Chojny-Dąbrowa	850.13	3,663.72	49.34	33.39	17.28	0.00	N
Dolina Łódki	1,408.94	405.23	99.92	0.08	0.00	0.00	N
Górniak	295.70	6,259.17	43.42	48.21	8.37	0.00	SW
im. Józefa Montwiłła-Mireckiego	25.70	3,351.72	7.72	92.28	0.00	0.00	SW
Julianów-Marysin-Rogi	826.96	1,562.95	97.91	2.09	0.00	0.00	N
Karolew-Retkinia Wschód	322.20	5,186.30	18.81	38.94	42.25	0.00	W
Katedralna	363.90	13,061.76	19.42	65.92	10.18	4.48	SW
Koziny	107.30	4,116.74	22.34	61.36	16.29	0.00	SW
Lublinek-Pienista	1,081.37	1,174.29	63.78	36.22	0.00	0.00	N
Łagiewniki	1,684.22	176.43	95.99	4.01	0.00	0.00	N
Mileszki	1,251.86	268.65	100.00	0.00	0.00	0.00	N
Nad Nerem	1,336.24	360.54	96.13	3.87	0.00	0.00	N
Nowosolna	1,557.55	489.70	95.89	4.11	0.00	0.00	N
Osiedle nr 33	798.95	1,127.51	95.71	4.29	0.00	0.00	N
Olechów-Janów	665.20	2,479.21	43.84	54.31	1.85	0.00	SW
Piastów-Kurak	218.31	4,939.48	32.72	35.29	31.99	0.00	SW
Radogoszcz	586.88	3,045.02	38.25	53.01	8.73	0.00	SW
Retkinia Zachód-Smulsko	378.05	3,612.32	42.84	37.64	19.52	0.00	N
Rokicie	597.27	2,482.99	63.24	20.39	16.37	0.00	N
Ruda	1,007.54	1,366.57	88.22	11.78	0.00	0.00	N

Auxiliary unit	Area [ha]	Pseudo-usable floor area [m²/ha]	N [%]	SW [%]	W [%]	WW [%]	Dominant class
Stare Polesie	586.50	7,574.69	27.52	65.34	7.13	0.00	SW
Stary Widzew	591.07	5,200.91	37.84	48.13	14.03	0.00	SW
Stoki-Sikawa-Podgórze	802.52	1,804.05	80.95	12.98	0.00	6.08	N
Śródmieście-Wschód	349.30	7,342.02	22.78	60.35	16.87	0.00	SW
Teofilów-Wielkopolska	458.43	4,104.19	23.21	50.53	26.26	0.00	SW
Widzew-Wschód	360.13	4,662.47	15.16	38.69	46.16	0.00	W
Wiskitno	1,670.75	785.36	99.76	0.24	0.00	0.00	N
Wzniesień Łódzkich	945.79	210.58	100.00	0.00	0.00	0.00	N
Zarzew	411.74	3,446.55	40.02	38.42	21.56	0.00	N
Zdrowie-Mania	567.90	1,235.27	75.67	24.33	0.00	0.00	N
Złotno	1,468.59	962.31	81.32	18.68	0.00	0.00	N

Source: own elaboration on the basis of BDOT10k data. N – low-rise, SW – medium-rise, W – high-rise, WW – very high-rise buildings

Taken together, the two strands of the results describe the same city at two different spatial and temporal resolutions, and the present data do not allow them to be joined into a single statistical model. The concentration series are annual values representative of the city as a whole, whereas the building-structure indicators describe a single cross-section aggregated by auxiliary unit. What can be stated is that the concentric structure of Łódź produces an unusually wide internal gradient of building intensity – from 13,062 m²/ha in Katedralna to 176 m²/ha in Łagiewniki – which is far greater than the between-year variation of any of the pollutants analysed. This suggests that in Łódź the spatial differentiation of exposure within the city may be more pronounced than its temporal variation, and that a citywide annual mean necessarily conceals it. Verifying this would require building-morphology indicators computed for the immediate surroundings of individual monitoring stations, which lies beyond the scope of the present study.

4. DISCUSSION

The concentration decreases recorded in Łódź were smaller than those reported for cities in southern Poland and, in contrast to the latter, none of the five trends reached statistical significance after correction for multiple testing. The decline in benzo(a)pyrene (−58.2%) was nevertheless the largest among the pollutants analysed, which is consistent with studies indicating that the replacement of solid-fuel heating appliances is the principal mechanism behind the reduction of this pollutant in Polish cities [19, 33].

The significant positive emission–concentration relationships obtained for NO_2 and BaP distinguish Łódź from the two remaining cities analysed in this research series. In the case of NO_2 this correspondence is plausible on physical grounds, since a substantial part of nitrogen dioxide emissions originates from sources that are reported and spatially concentrated within the city. It should nevertheless be emphasised that the KOBiZE data cover reported industrial sources rather than total urban emissions. The sensitivity checks in Section 3.2 show that both associations are stable to the omission of single years, but that they cannot be clearly separated from the parallel decline of both series: for NO_2 the association beyond the trend rests mainly on the joint maximum in 2021, and for BaP reported emissions decreased in every year.

The absence of significant meteorology–concentration relationships does not indicate that meteorological conditions are irrelevant, but reflects the resolution of the analysis and its statistical power. Annual means average out the multi-day episodes during which the influence of weather on concentrations is greatest, and with seven observations and correction across 15 pairs the detection threshold is high. The narrow range of annual mean wind speeds recorded in Łódź (3.0–3.3 m/s) may additionally have limited the variability on which such a relationship could be detected. The inhibition

of air inflow into the city by the Łódź Hills, described in earlier work on the local climate of the city, operates on precisely the episodic time scale that annual aggregation conceals [28, 29].

The height structure of development in Łódź, described by the pseudo-usable floor area indicator, is dominated by low-rise buildings (48.51%), whose share is nevertheless considerably lower than that obtained on the basis of the number of buildings (90.86%). The concentric structure of the city is clearly reflected in the spatial distribution of building intensity: the highest values were recorded in the central units of Katedralna and Stare Polesie, whose compact nineteenth-century fabric is a direct legacy of the industrial development of the city, and in the large housing estates of Widzew-Wschód and Karolew-Retkinia Wschód. The contrast between these areas and the peripheral units, where building intensity is lower by up to two orders of magnitude, is greater in Łódź than in the remaining cities analysed and is a consequence of the administrative extent of the city, which encompasses substantial agricultural and forest areas [13, 14].

The practical significance of the changes recorded here becomes clearer when the 2024 values are compared with the standards laid down in the revised Ambient Air Quality Directive, which entered into force in December 2024 and must be met by 2030 [34]. In Łódź, C_6H_6 (1.13 μg/m^3) remained well below its limit value of 5 μg/m^3 and the annual mean NO_2 concentration of 13.7 μg/m^3 was already below the 2030 limit value of 20 μg/m^3, but BaP exceeded its target value of 1.0 ng/m^3 by 90%, PM_{10} exceeded its limit of 20 μg/m^3 by approximately 53%, and $PM_{2.5}$ exceeded its limit of 10 μg/m^3 by about 62%. The compliance problem in Łódź is therefore concentrated in the particulate and polycyclic aromatic fraction rather than in nitrogen dioxide, which is the reverse of the pattern observed in Kraków.

This distribution of exceedances is consistent with the source structure implied by the results. The decline in BaP concentrations accords with solid-fuel combustion being the principal contributor, in line with national monitoring evidence for this pollutant [19, 33]; the BaP emission–concentration association cannot by itself support this attribution, because it cannot be separated from the common trend. At the same time, PM_{10} concentrations ceased to fall after 2022 and rose slightly in 2023–2024, whereas reported PM_{10} emissions continued to decline – a divergence that reported industrial emissions alone cannot explain and that most plausibly reflects the contribution of diffuse sources and of inflow from outside the city [14, 27].

4.1 Limitations

The analysis is based on seven annual values for the city as a whole. This limits both the precision of the results and the possibility of separating the influence of time from that of weather. The KOBiZE data cover reported industrial sources rather than total urban emissions, and municipal and residential combustion – the dominant source of BaP in Polish cities [19] – is therefore represented only indirectly. The concentration series come from two monitoring stations and do not represent a spatial mean for the whole city, whereas the emissions refer to the entire city area. Because reported BaP emissions decreased in every year, the BaP emission–concentration association cannot be separated from the common trend. The building-structure indicators were aggregated at the level of 36 auxiliary units, whereas the concentrations are point measurements at monitoring stations aggregated to the scale of the whole city; the results therefore describe the co-occurrence of urban form and air quality at the city scale and do not permit conclusions about the immediate surroundings of individual stations. Consequently, the results describe changes within the analysed period but do not allow their causes to be established.

5. CONCLUSIONS

1. Between 2018 and 2024 the mean annual concentrations of all five air pollutants analysed in Łódź decreased; the largest declines were recorded for benzo(a)pyrene (−58.2%) and nitrogen dioxide (−43.0%).
2. None of the five monotonic concentration trends reached statistical significance after Benjamini–Hochberg correction; the smallest corrected p-values were obtained for BaP and PM_{10} (pBH = 0.0595 in both cases). The results therefore document lower concentrations in 2024 than in 2018, but the course of the decline over the whole period is not statistically confirmed.
3. Significant positive relationships between reported emissions and concentrations were found for NO_2 and BaP, which indicates that the years with higher reported emissions also tended to be the years with higher concentrations of these pollutants. Both associations were stable to the omission of single years, but neither can be clearly separated from the common downward trend, so they do not establish an effect of the reported emissions.
4. None of the 15 meteorology–concentration relationships was significant after correction for multiple testing. The small number of observations and the narrow range of annual mean wind speeds in Łódź (3.0–3.3 m/s) may have limited the detection of such relationships, but the analysis does not show that they caused the absence of significance; the result is therefore not evidence that meteorological conditions are irrelevant.
5. The concentric structure of Łódź is clearly reflected in the spatial distribution of building intensity: the pseudo-usable floor area per hectare ranges from 13,062 m^2/ha in the central Katedralna unit to 176 m^2/ha in peripheral Łagiewniki. The share of low-rise buildings decreases from 90.86% of their number to 48.51% of the pseudo-usable floor area, which demonstrates the importance of the vertical dimension of development for the assessment of urban structure.
6. The concentration analysis and the characterisation of building structure remain separate findings. Their juxtaposition indicates that, despite the decrease in pollutant concentrations over the analysed period, the marked differentiation in the intensity and height of development in Łódź may influence local ventilation conditions and the spatial distribution of pollutants; the available data, however, do not allow this relationship to be confirmed or its strength to be determined. The results primarily indicate the direction of further research, which requires concentration measurements to be spatially linked with building parameters.

ADDITIONAL INFORMATION

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