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Original Research Article

ANALYSIS OF LIGHT POLLUTION OF THE NIGHT SKY IN TORUŃ (POLAND)

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Abstract

Light pollution is one of the types of environmental pollution. The sky illuminated by the excessive light emission is an inherent element of the modern world. This phenomenon has been known for over a century, but research has been carried out only for several decades. Analysis of the brightness of the sky was made for Toruń (Poland) and neighboring areas. The main aim of the study was to study the distribution of brightness of the sky over a medium-sized city. The basic research method was a direct measurement of brightness made with the SQM photometer. The conducted research was carried out throughout the calendar year on 24 measurement stations located in Toruń. Measurement stations represented various types of buildings occurring in every city. On the basis of the obtained data, a map was made showing the extent of light pollution and its intensity, as well as the spatial distribution of this phenomenon. The brightness of the sky was also examined in terms of astronomical and weather conditions. Each aspect is documented in tabular and visual form.

Keywords: light pollution, SQM, land cover, Toruń, Poland

1. INTRODUCTION

The world around us is becoming increasingly polluted and the effects of this pollution are becoming more and more manifested. People, plants and animals are

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directly affected by the deteriorating conditions of the environment [10]. The forms of pollution well known to most people are thoroughly research and the results of these studies are made public. These include, inter alia, air pollution (e.g. particulates and ozone), water and soil pollution (e.g. pesticides and heavy metals), landscape pollution, noise pollution and radioactive contamination [22,24,33,30,31,32,36]. Every responsible person on our planet has some basic knowledge of these issues. However, we live and function in the environment exposed to the impact of other and previously unaddressed pollutants, of which we are not aware that they may have a significant negative impact on our functioning and health.

It has only recently been observed that light pollution is a form of environmental pollution that was not previously considered in scientific research. Targeted research, together with regular monitoring, did not start until the end of the last century. In Poland, this type of research is carried out only by several academic scientific centres [29]. Recently, however, research on light pollution has intensified and is becoming an increasingly popular research topic [9]. This phenomenon has not yet been fully researched in a comprehensive and multifaceted way, and not all the factors and parameters related to its occurrence have been determined. The in-depth study of the subject requires interdisciplinary work of scientists from a wide range of scientific disciplines and the establishment of a common measurement network.

The brightness of the sky at night is determined by several factors, including i.a. land development, cloud cover or time of year in which observations are made [9,13,29]. The research carried out in Toruń (Poland) and the performed analyses were aimed at a preliminary assessment of the impact exerted by the above-mentioned factors. They were preceded by extensive observations of the night sky pollution in the summer season [12].

2. LIGHT POLLUTION

The phenomenon of light pollution differs from other known types of ecosystem contamination in that the factor causing it is light, which is not usually attributed to the negative effects of human activity [10] or associated with something negative or dangerous [26]. What is more, light is considered to be something good; we surround ourselves with light throughout all our daily activities.

Few people are aware that deviating from the daily cycle and increasing the amount of light at night have a very negative impact on our health [10,15]. Excess of this factor may cause hormonal disorders, metabolic problems, melatonin deficiency as well as deterioration of sleep quality and slow-wave sleep deprivation in humans [6,11,27,28]. This has also negative consequences for the development of plants and the functioning of animals [4,5,6,8,11,18,19,21,28,35].

Today, more than 60% of Europeans and over 80% of US residents live in areas with high levels of light pollution [3,8,35]. This is becoming a contemporary problem for urban dwellers who are unable to observe the countless star constellations directly at their place of residence, not to mention the possibility of enjoying the view of the Milky Way; all because of the bright glow.
Light pollution can be measured in a number of ways and the employed methods can be divided into observational and instrumental ones, but unlike other forms of pollution, both amateurs and specialists can measure this phenomenon [2,7,17,20,25]. In this project, the measurement was performed using the SQM L-version photometer produced by the Canadian company Unihedron, owing to which our results could be compared with those obtained by other research teams around the world [7,9,10,13,14,23,29,34].

3. MEASUREMENT NETWORK

In order to investigate the phenomenon, measuring stations (in this study also referred to as sites) have been established to form a network throughout the city. The stations have been selected so as to meet all the measurement and design requirements. Toruń was selected as a study area, which is a medium-sized city, the structure of which encompasses all characteristic types of urban development.

3.1. Study area

Toruń is a medium-sized city, founded in the Middle Ages, with a population of almost 185,000 people. It is located at the Vistula River in the central part of the Kujawy-Pomerania Province. The urban area of the city has been divided into 24 housing estates, each of them distinguished by characteristic development. The area of the city is less than 116 km^2, and its recognisable element is the Vistula River, which divides the city into two asymmetric parts – the right bank with 18 housing estates and the left bank with six estates. The city is surrounded by numerous small towns and villages, which have recently developed significantly and become an attractive destination for people migrating from the city centre.
We can distinguish several characteristic types of housing in Toruń. These include both high and medium multi-family housing, as well as dense downtown development, single-family housing, industrial and commercial housing development and open land. Each of these types dominates in a specific part of the city. The characteristic downtown development is perfectly visible in the strict city centre (Fig. 1A).
In selected residential districts one can observe high-rise multi-family housing characterised by multi-storey buildings. They are located in the central-eastern part of the city. These places are characterised by intense illumination of frequently used sidewalks and streets, which are mostly the main arterial roads of

the city, making the street lights even more dazzling (Fig. 1B). Street lamps are densely arranged and spaced to create a uniform glow.

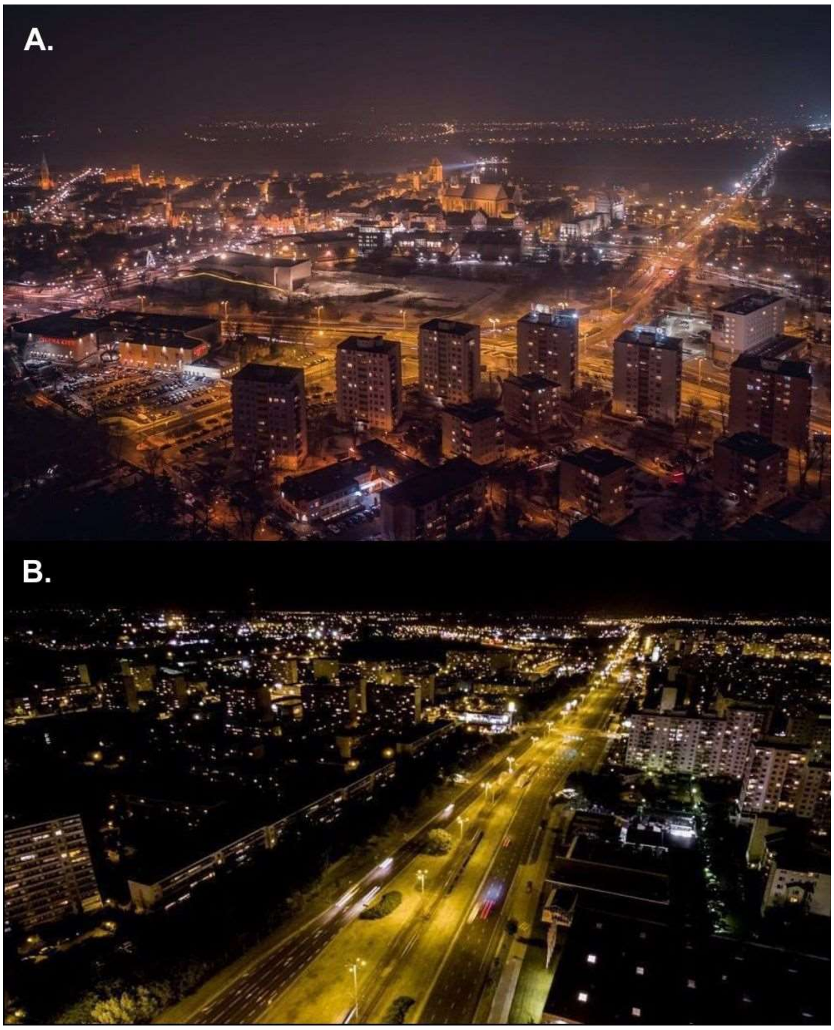

Fig. 1. Examples of illuminated areas in Toruń: A) Toruń Old Town (source: https://farm5.static.flickr.com), B) Photo of the main arterial roads of the city: Szosa Lubicka by night, (source: https://filmsky.pl/portfolio/lubicka-noca-dron/)

Single-family houses are located in several independent parts of the city. Typical elements of these areas are low, evenly spaced buildings located on plots of about 600–1000 m^2 and rows of street lamps along the passageways. Even though there is much less illumination here, numerous and low lamps illuminate the entire traffic routes resulting in a uniform glow. Industrial or commercial areas are an integral part of every city. In Toruń, this type of development is located on the outskirts of the city and occupies relatively extensive areas in the north-eastern and western parts of the city. In terms of light emission, these areas have two ambivalent characteristics: on the one hand, they feature open areas that emit much less light and, on the other, they are intersected by well-illuminated roads and squares. Open areas are also found in the southern and northern parts of Toruń. Their characteristic feature is a large distance to any compact commercial or housing developments, or illuminated roads. The lowest sky brightness is expected to be observed in these areas due to the lack of emissivity from the land cover and the largest part of the sky not covered by anthropogenic objects.

3.2. Assumptions and conditions of the measurements

The main objective of the conducted research was to measure and analyse the light pollution in Toruń. The results of the measurements were analysed in relation to specific types of land cover in the immediate vicinity of the measuring stations. In order to meet the assumptions and achieve the objective of the project, a uniform, representative and easily accessible measurement network was established in Toruń. While planning the measurements, it was necessary to ensure the same weather and astronomical conditions, so that both the measurements and analyses were as repeatable, comparable, correct and accurate as possible. The measurements were performed during the astronomical night, which is the time when no influence of sunlight on the brightness of the sky is observed (Fig. 2). In the summer season [12], however, this phenomenon does not occur at the latitude corresponding to the location of Poland, therefore the measurements were made when the position of the Sun under the horizon was the lowest.

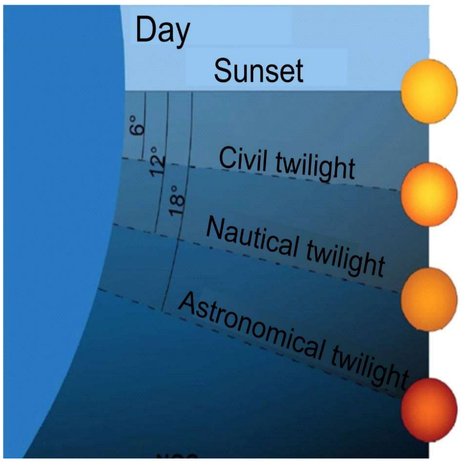

Fig. 2. Three types of twilight

The diagram below shows the measurement at one selected site. This proves that the assumptions regarding the registration during the specific part of the night are correct (Fig. 3).

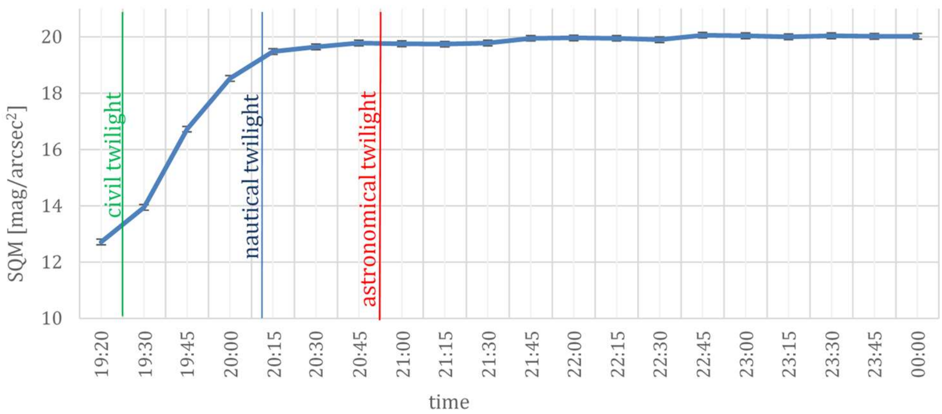

Fig. 3. Sky brightness measurement taken at one station on September 19, 2017

The following assumptions were made when establishing the observation network consisting of measuring stations:

- regular distribution of the stations throughout the city,
- transport accessibility,
- representation of different land-cover categories,
- representation of specific types of land development,
- the presence of a relatively small number of obstructing elements in the form of trees or building façades,
- location as far away from street and neon lights as possible, so that the measurements are not artificially inflated.

Before starting the measurements, each site was checked for measurement conditions, both during the day and at night [7]. In addition, four reference sites were selected outside the city limits, which served as a reference (background) for measurements in the urban area of Toruń. After taking into account all the assumptions and objectives, a measurement network consisting of 24 sites was created in Toruń (Fig. 4).

The land cover of the designated measuring stations was initially determined based on the publicly available General Geographic Database (GGD) on a scale of 1:250,000, the CORINE Land Cover classification from 2012 and data obtained as part of the Urban Atlas created by the EEA for the Toruń – Bydgoszcz urban agglomeration (Fig. 5).

However, the suggested classification options were insufficiently accurate with respect to the assumptions of the project and therefore we decided to use our own classification of land cover on a scale 1:10,000 prepared for the purposes of another project carried out in Toruń [16] (Fig. 6).

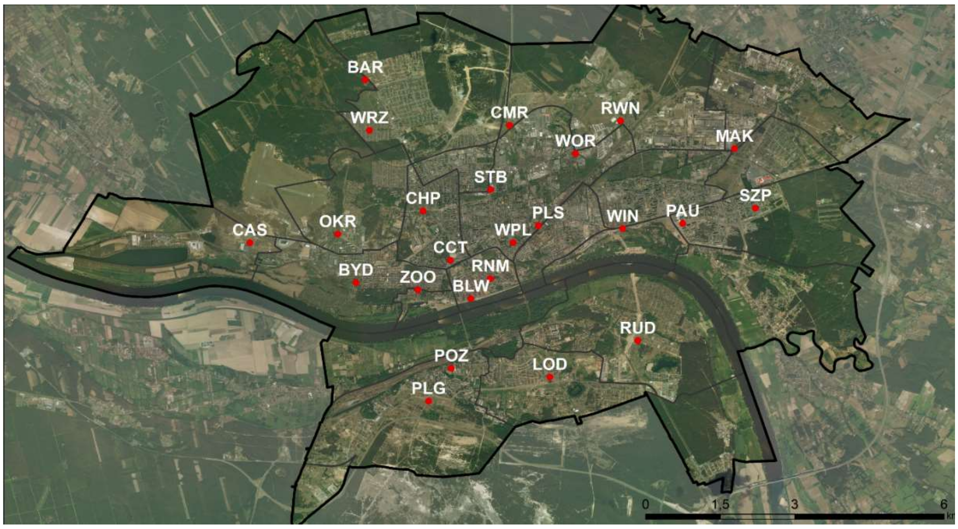

Fig. 4. Location of measuring stations in Toruń

The established measuring stations were assigned to the distinguished land-cover classes. Table 1 shows the selected classes of land cover with the corresponding measuring stations.

Table 1. List of measuring stations divided into dedicated classes

Classification of land cover		Number of measuring points	Measuring stations
city buildings	inner-city buildings	2	**BLW RNM**
	single-family housing	2	**BAR WRZ**
	block building	5	**CHP ZOO PAU SZP WPL**
industial buildings	industrial, construction and road-rail areas	1	**CCT**
	industrial and warehouse buildings	6	**OKR POZ RWN WOR PLS STB**
Open area	thickets, allotments, grassy vegetation	3	**WIN MAK CMR**
	forest and other tree stands	1	**BYD**
	sandy or pebble areas	3	**CAS PLG RUD**

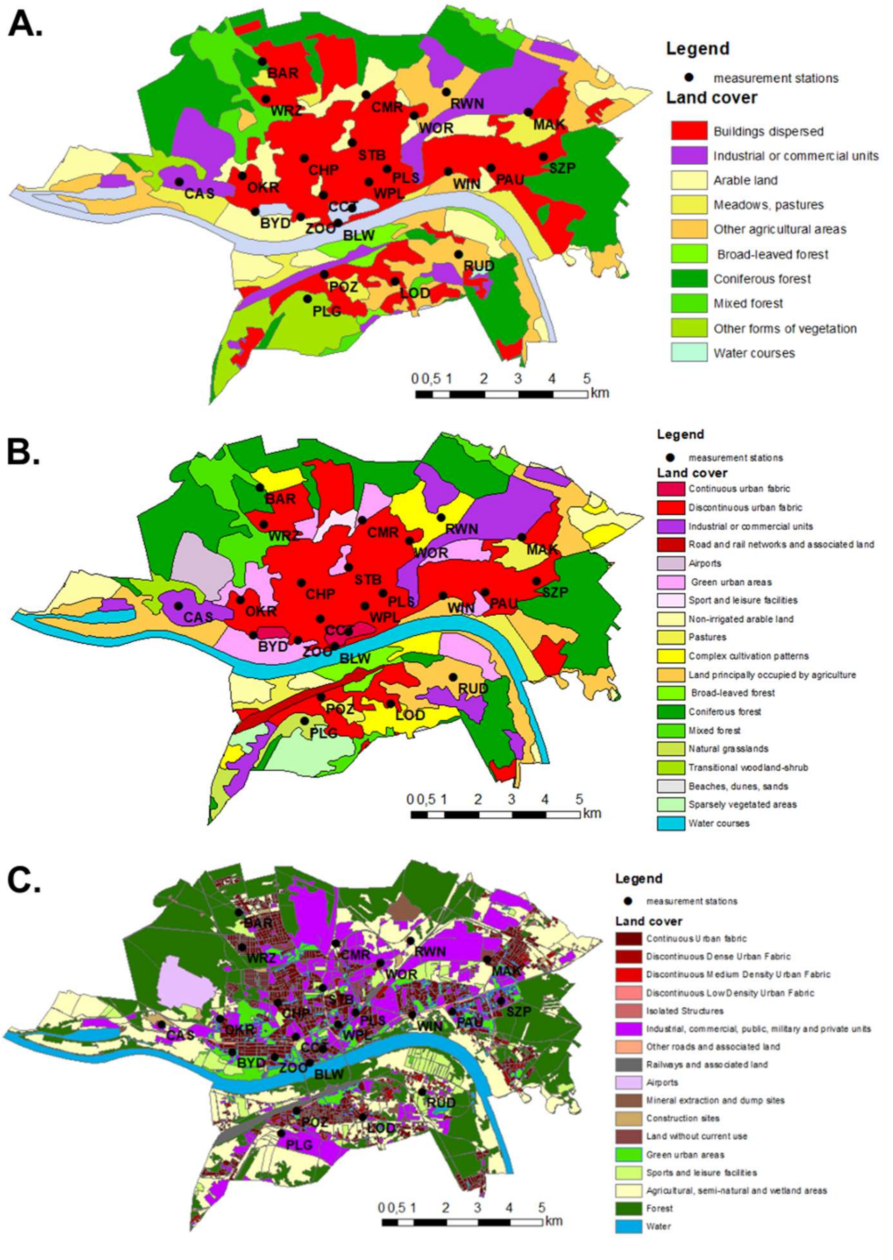

Fig. 5. Available land cover databases for the area of Toruń: A) General Geographic Database corresponding to the detailed scale of 1: 250,000, B) CORINE Land Cover of Toruń, C) Urban Atlas created by the EEA for the Toruń – Bydgoszcz urban agglomeration

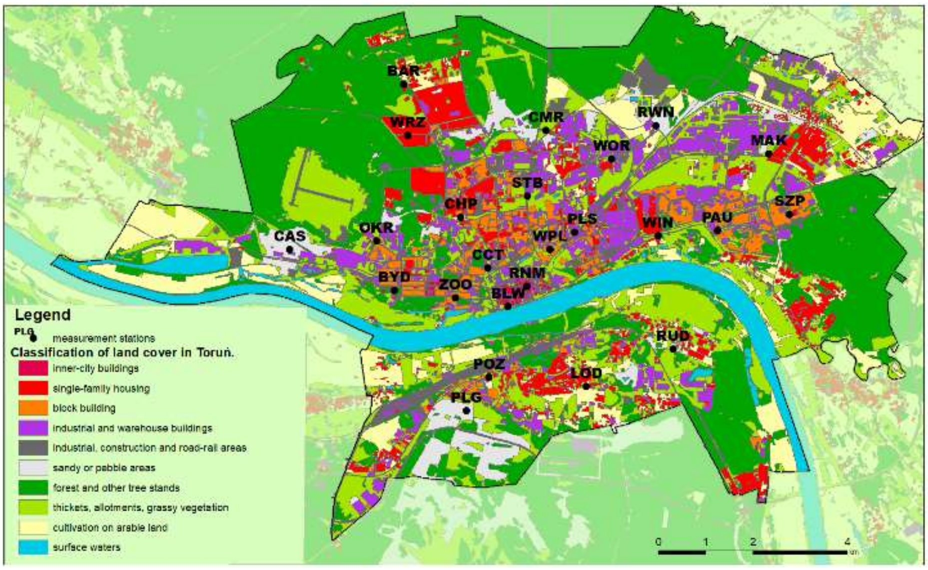

Fig. 6. Map of land use/cover of Toruń on a scale of 1:10,000

In order to assess the diversity of land surrounding the measuring stations, an analysis of visualization in 100 m buffer zones was also developed. The selected sites representing different land cover categories are presented in Figures 7A to 7B.

4. RESULTS AND INTERPRETATION OF THE OBTAINED RESULTS

After verification of the factors affecting the measurements and establishment of the observation network, the night sky brightness measurements were commenced and continued for the next 12 months, i.e. from early June 2017 to late May 2018. During this time, a total of 36 measurement sessions were carried out (one measurement session was not finished due to a sudden rain), which can be classified as follows:

- 21 measurements with a slightly clouded sky and 14 measurements with a mostly cloudy sky and overcast,
- eight measurements in spring and nine measurements in summer [12], in autumn and in winter.

A total of approximately 1,700 km were covered during all measurement sessions. It is a distance approximately equal (in a straight line) to the distance between Warsaw and London or Warsaw and Montenegro.

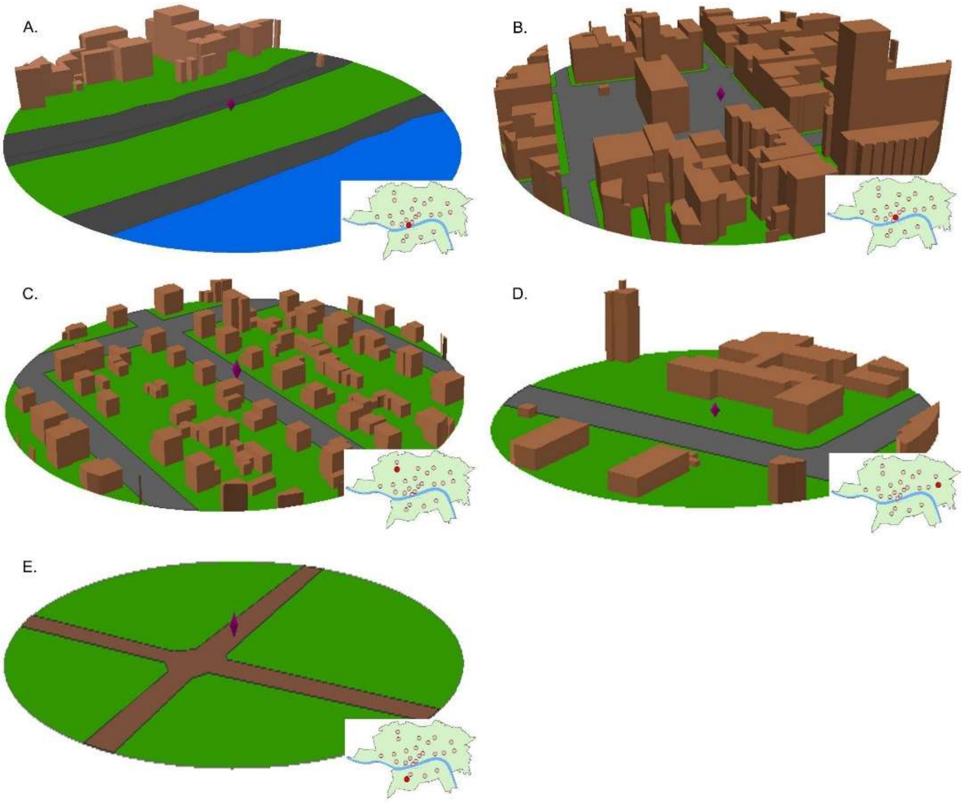

Fig. 7. Measuring station – selected examples of the point surroundings within 100 m A) Philadelphia Boulevard (BLW), B) Rynek Nowomiejski in Old Town (RNM), C) Wrzosy district, Jastrzębia Street (WRZ), D) Kosynierów Kościuszkowskich Street near Primary School (SZP), E) Generała Andersa Street – road to the polygon (PLG). (visualization in the ArcGIS software)

The spatial distribution of light pollution in Toruń was derived from the obtained measurement results, i.e. annual and seasonal mean values of the sky brightness. The data were interpolated using the kriging method in the ArcGIS (Esri) software, which enables extensive and multi-faceted spatial analyses. Figure 8 presents the result of sky brightness data interpolation.

When analysing the above collation and spatial distribution, we can distinguish three areas on the map of Toruń with clearly greater brightness of the sky: the strict city centre as well as the north-western and eastern parts of the city. In other areas, the sky brightness clearly decreases. Values measured at the measuring stations range from 14.4 mag/arcsec^2 to 18.2 mag/arcsec^2, which is about 4 units of difference and about 40 times brighter skies.

The results obtained from the measurements were also analysed in relation to the developed land cover classification. The average night sky brightness values from each measuring station were assigned to the land cover categories. Table 3 shows these correlations with additional consideration of cloudy and cloudless days.
It is worth noting that the brightest sky is observed in areas with single- and multi-family housing development, and in the downtown zone, with an average value of about 15 mag/arcsec^2, whereas the darkest sky is observed in open and green areas, with an average value of 18 mag/arcsec^2. The measured value also clearly increases during days a cloudless sky. The largest difference was recorded at the sites located far from the city centre – over 1.7 mag/arcsec^2. The opposite situation is observed at the highly illuminated sites, located in the city centre in the single- and multi-family housing estates and in the downtown zone; the difference here is about 0.5 mag/arcsec^2.

Table 2. Average brightness of the sky on every station

CODE	**Average brightness of the sky [mag/arcsec^2]**
BAR	15.34
WRZ	16.21
CHP	17.34
OKR	17.72
CAS	18.13
BYD	17.64
ZOO	16.35
BLW	16.78
RNM	16.01
CCT	15.79
POZ	17.52
PLG	18.15
LOD	17.39
RUD	17.61
WIN	17.14
PAU	16.17
SZP	15.61
MAK	17.12
RWN	16.98
WOR	17.41
PLS	15.17
WPL	14.41
STB	15.54
CMR	17.85
Average	**16.70**

Both the spatial distribution (Fig. 8) and the tabular data collation (Table 3) show that the results obtained at each station in the city of Toruń range from between 14 and 19 mag/arcsec^2.

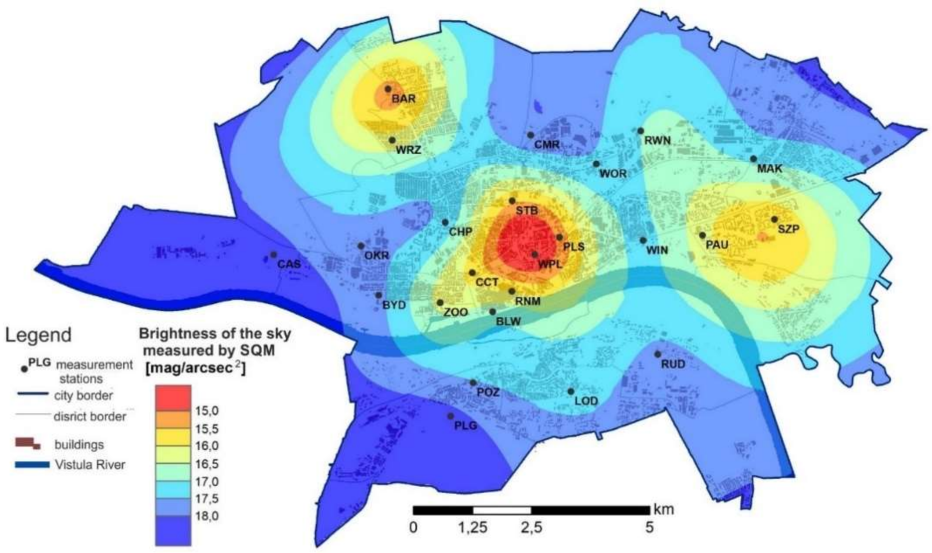

Fig. 8. Spatial distribution of the light pollution in Toruń

Table 3. Average measured brightness of the sky in relation to the type of land cover

Measuring stations	Classification of land cover	Average all year round [mag/arcsec^2]		
		general	cloudy	without cloud cover
BAR WRZ	single-family housing	15.77	15.48	15.96
CCT	industrial, construction and road-rail areas	15.79	15.44	16.08
CHP ZOO PAU SZP WPL	block building	15.97	15.34	16.44
BLW RNM	inner-city buildings	16.39	15.69	16.96
OKR POZ RWN WOR PLS STB	industrial and warehouse buildings	16.72	16.11	17.23
WIN MAK CMR	thickets, allotments, grassy vegetation	17.37	16.47	18.06
BYD	forest and other tree stands	17.64	16.60	18.43
CAS PLG RUD	sandy or pebble areas	17.96	17.00	18.73

The results of measurements carried out in Toruń are consistent with those obtained in other cities of Europe and worldwide [9,23,29]. The research group carrying out measurements of sky brightness in Hong Kong obtained an average value of about 15.9 mag/arcsec^2 in urbanized areas and 18.4 mag/arcsec^2 in areas far from the city. Similar results were also obtained by a group of scientists studying pollution in Kraków [29]. At the sites located in the city centre, they obtained measurement results at the level of 13.5 mag/arcsec^2, while at the sites located far from the centre, the values reached 20.5 mag/arcsec^2. The data collected during those measurements are also consistent with the results obtained in Toruń on days with different degrees of cloudiness. In the research conducted in Kraków, the difference between measurements on cloudless days and on overcast days at sites located in the city centre is 1.5 mag/arcsec^2, while at sites located outside the city – 2 mag/arcsec^2.

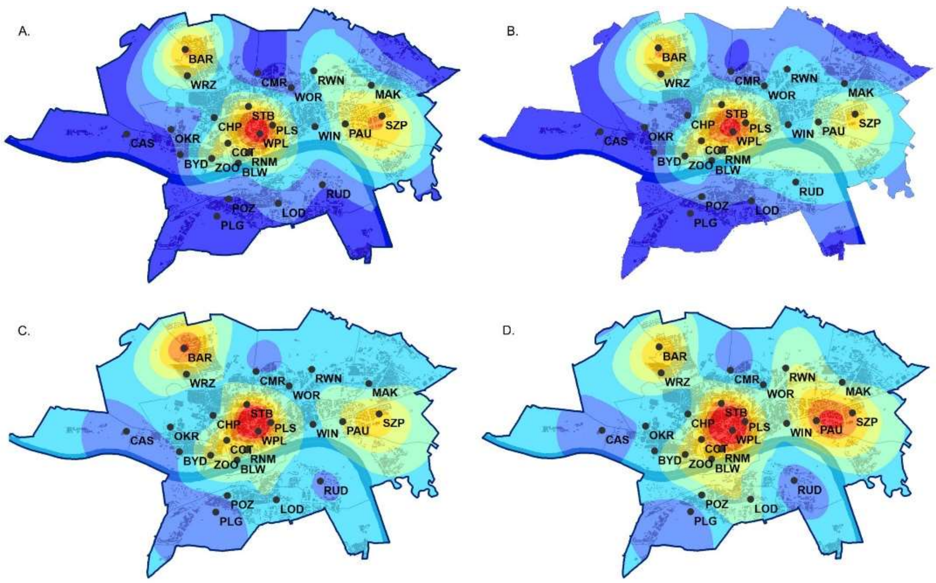

Fig. 9. Spatial distribution of the brightness of the sky over Toruń in relation to the observation seasons, from spring to winter: A) spring season, B) summer season, C) autumn season, D) winter season

For the purpose of comparison and to illustrate how dark the sky can be, we can refer to the value obtained in the La Palma observatory area, which was over 22 mag/arcsec^2 [1]. Almost the same result (21 mag/arcsec^2) was also measured at Xinglong Observatory, in China [14]. We can therefore see that the sky observed in Toruń even on the darkest days only seems dark to us.

Another aspect analysed in our study was the analysis of sky brightness in relation to the season. Figure 9 present the results of the research in this area in relation to the observation seasons, from spring to winter.

On the basis of these figures we can conclude that the spatial distribution of light pollution does not change significantly throughout the year. In each case, we see three characteristic areas with higher light pollution, but the intensity of the examined phenomenon varies seasonally – the brightness of the sky increases in the autumn and winter seasons.

The same conclusions were reached by scientists from the Kraków University of Technology in Poland who carried out measurements in Kraków [29], the difference between measurements made in the summer and winter season was on average 2.5 mag/arcsec^2.

The graphs with the obtained results broken down by the observation seasons are interesting. The stations were arranged according to the distance between the measuring point and the illuminated road and buildings (Figs. 10–13). The results were divided into measurements on mostly cloudy days (darker column) and slightly cloudy days (lighter column) in relation to the total average value calculated from the data measured in a given season.

It is worth noting that in places with a darker sky the difference in readings between a mostly cloudy day and a slightly cloudy day is up to 2 mag/arcsec^2, which corresponds to up to 6 times brighter skies. In places where the sky is very bright, the difference is relatively small.

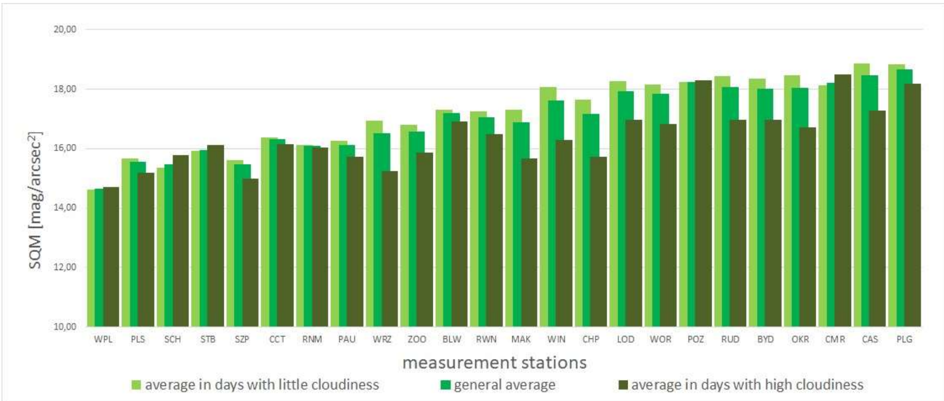

Fig. 10. Average values of the sky brightness measured with the SQM photometer in spring

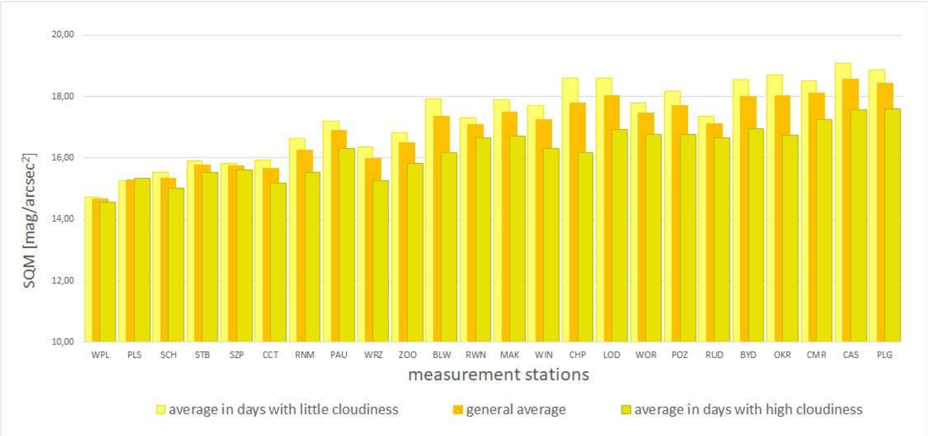

Fig. 11. Average values of the sky brightness measured with the SQM photometer in summer

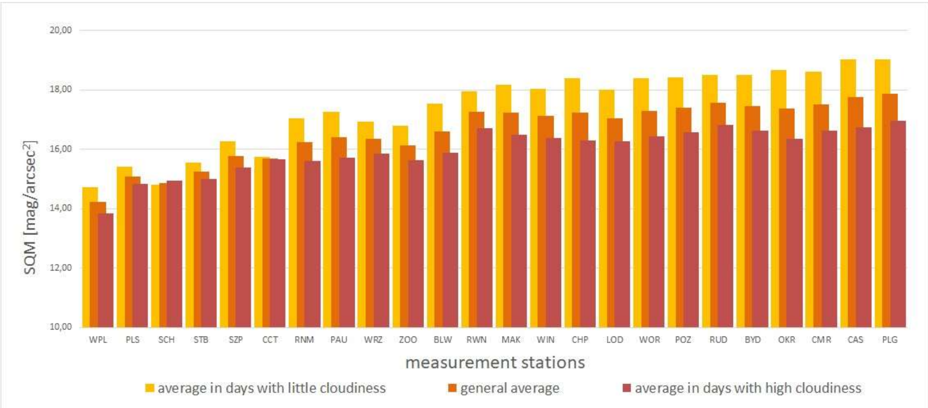

Fig. 12. Average values of the sky brightness measured with the SQM photometer in autumn

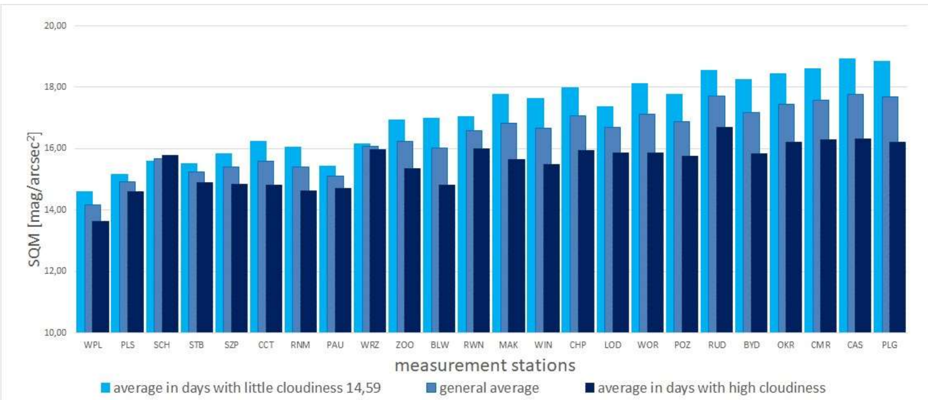

Fig. 13. Average values of the sky brightness measured with the SQM photometer in winter

5. CONCLUSIONS

Light pollution is becoming an increasingly common phenomenon, subject to observation and monitoring in many places of the world. Researchers from different institutions are increasingly interested in this phenomenon in terms of both its causes and effects, making it an interdisciplinary issue with high social responsibility. As a result, diverse research methods have been developed, the measurement network is becoming increasing denser and advanced visualizations of acquired measurement data are used.

The measurements show that the increased brightness of the sky at night is determined by a number of factors, including cloudiness, season and land cover in the immediate vicinity of a given observation site. Based on the obtained results, it can be concluded that the brightest values are characteristic for areas with dense single- and multi-family residential housing and downtown developments. This is due to a significant number of street lights and the presence of illuminated billboards and neon lights. On the other hand, the darkest places are open areas and adjacent industrial areas, usually located on the outskirts of the city. The conditions for the dark sky observation are improved in such places by a long distance to an illuminated street and scattered development. The results of measurements carried out in Toruń are consistent with those obtained in other cities [9,23,29].

It has been observed that in places with significant light pollution, like in the city centre, neither the season of the year nor the degree of cloudiness had significant impact on the measurement of the sky brightness. These factors, on the other hand, significantly affected the measurements in areas with a darker sky, almost bringing the results closer to highly urbanised areas.

The issue addressed in this paper is a relatively new one, researched by scientists working in miscellaneous fields. It is therefore necessary to study the phenomenon in depth in order to identify its limitations and to learn about its impact on the surrounding environment.

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