Edited by Tomasz Ścieżor

Light pollution and its impact on the natural environment

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Editor’s note

In recent years, the pollution of the night environment with artificial light, referred to as light pollution, has become increasingly noticed and treated as one of the civilization threats. Different categories of light pollution are distinguished which directly or indirectly affect the natural environment, including affects on humans. Among the many aspects of the impact of light pollution, the following can be identified:

- the effect of light pollution on flora and fauna;
- the effect of light pollution on astronomical research;
- the impact of architectural management with regard to limiting light pollution;
- meteorological aspects of light pollution;
- methods of reducing light pollution and minimising its effects;
- dark sky tourism in the context of light pollution;
- shaping public awareness of light pollution;
- economic aspects of light pollution.

As a result, an increasing number of scientists, including biologists, ecologists and astronomers, as well as architects and representatives of local governments, are interested in the issue of protection against light pollution or reducing its impact on the environment. Nevertheless, literature on the subject remains dominated by works related to only one specific scope of this impact. Noting the multidisciplinary nature of the subject as well as the need to ensure the exchange of information between researchers representing various fields of science in different countries, in 2021, the first multi-author monograph “Ecological and astronomical aspects of light pollution” was published at Cracow University of Technology, addressing various aspects of the issue of light pollution.

This monograph, which is a continuation of the topic initiated by the above-mentioned publication, contains chapters discussing both the issues of measuring the level of light pollution, as well as ways to reduce it and its impact on living organisms.

At this point, thanks should be given to the people who made this monograph possible. Among the many people involved in its creation, mention should be made of: Bartosz Balcerzak, Miroslav Kocifaj, Sylwester Kołomański, Andrzej Kotarba, Marek Kubala, Anna Młyńska, Katarzyna Szlachetko, and Bronisław Wołoszyn.

Editor,
Tomasz Ściężor

1. Why are we becoming increasingly addicted to high levels of illuminance and how is this affecting light pollution

Małgorzata Bartnicka*

For hundreds of thousands of years, the ancestors of modern man lived in harmony with the natural rhythm of day and night, i.e. with the presence and absence of sunlight. The first breakthrough came with the conscious use of fire, which contributed to the extension of the "duration" of day. Later, several additional means such as campfires, torches, oil lamps and candles were used. Unfortunately, a single flame equivalent to several lux did not give out lighting good enough to perform certain activities. Therefore, the general solution was to strengthen the luminous flux by increasing the number of light points and by using reflectors. Until the mid-nineteenth century, every new discovery related to lighting was based on an open flame (e.g. gas or kerosene lamps). At the turn of the eighteenth and nineteenth centuries, everything changed when electric current was discovered, initially through the use of arc lamps (approx. 1850) and then in the first light bulbs.

For the last 150 years, humanity has lived in the light of a light bulb, whose spectrum is similar to sunlight due to the way it produces light through combustion, or more precisely, through the glowing process. The obtained levels of illuminance were high enough to illuminate the darkness of the night for good. This brought about the first significant change in people's habits and lifestyles. Suddenly, it was much lighter, and it was giving out the levels of illuminance which had previously been unknown. Subsequent light sources introduced since the beginning of the twentieth century were no longer associated with fire and the methods of emitting light were based on other physical phenomena ranging from gas electrical discharges to luminescence.

The search for new sources of lighting has always had one basic goal – to create a light source similar in spectral range to sunlight, which would at the same time be energy-saving and emit as much light as possible. This development, combined with the expansion of other technologies related to light emission, has led to people becoming "addicted" to high levels of luminance and illuminance.

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Aim and method

The aim of the article is to show how people's demand for light and higher levels of illuminance have increased over several decades. As a basis for this study, a series of regulations and norms specifying the legally required levels of illuminance have been investigated. A comparative analysis of the recommendations contained in Polish standards from 1934 onwards was performed. The results of this analysis are presented in Table 1.1. Subsequently, an attempt was made to explain what factors may contribute to the increased demand for high levels of illuminance.

Table 1.1. A list of recommended levels of illuminance for some activities in selected Polish lighting standards

Illuminated space or nature of the activity	Illuminance levels [lx] recommended by the standards of specified years						
	PNE-44 1934	PN-E-02030 1952	PN-E-02030: 1957		PN-E-02033 1968	PN-E-02033 1984	PN-EN-12464 2003
			standard light bulbs	fluorescent lamps			
vestibules, stairs, corridors, entrance halls	2–5	20–50	20	–	50	50	50
living rooms, kitchens, bathrooms (throughout the room) – kitchens	20	20–50	20	50	70	100–200	200
kitchens – worktops, kitchen islands	40	50–100	bd	bd	300	300	500
leisure reading and writing, searching for books on the shelves	30	50–100	50	100	100–150	200	300
office activities, reading and writing for long periods of time, activities that require detailed work	40	100–200	100	200	200	300	500
student classroom activities, the area of student desks	50	100–200	100	200	300	500	500
work that requires distinguishing small details, e.g. drawing, technical drawing	80	200–500	200	300	300–500	750	750
work that requires distinguishing small details, e.g. engraving, watchmaking, sewing, stitching	80	200–500	300	500	300	500	750

Compiled by the author.

Discussion and conclusions

The essential requirement for performing a task in an efficient manner is an appropriate level of illuminance. This is standardised by law. The demand for the amount of light for certain activities has always been variable, depending on the activity performed. It began to be normalised only when electric light sources were invented, and artificial light began to be used for shift work as another factor in the drive of the economy.

The way we have been determining such illuminance has been evolving over time. The process of normalisation of lighting began in the early twentieth century. The first country to create standards for "light brightness"[1] levels was the United States, which was the first to issue a "Code of Lighting" in 1915 (New Jersey 1918). By 1935, recommendations were also made in European countries. In Poland, general lighting standards for interiors were developed in 1934 by the Polish Committee on Illumination (CIE Poland) (PNE 1933). The starting point for determining "the averages of brightness" was the adoption of minimum values that must not be exceeded so as to not expose the employee to health issues. A list of recommendations of individual Polish lighting standards is included in Table 1. The Polish PNE-44 standard from 1934 seems very lenient in terms of recommendations for illuminance levels in comparison with the US regulations of 1915. In the mid-nineteen-forties, it was decided to revise Polish lighting standards. The pioneer of post-war activities was the Ministry of Labour and Social Welfare, which in 1946, published a brochure "Light and Work" by Ignacy Baran (Baran 1946).

As a result of the activities of the Department of the Ministry of Industry and Trade, the XXVIII Lighting Commission was established, whose task was to amend and supplement the Polish brightness standard PNE-44/1934. The basis for the development of the first "recommendations for brightness levels" was the rationality of lighting at workplaces, where research was focused on efficiency and the number of mishaps and accidents, in accordance with the slogan: "good lighting fights accidents". The result of the committee's work was the standard published in January 1952: PN-E-02030:1952 (PN-E 1952). The proposed limits of the illuminance range were defined for reasons of occupational hygiene and safety (lower limit) or due to the operating costs of lighting devices (upper limit). According to this standard, a level of illuminance above 100 lx could be obtained by means of local/spot lighting while maintaining general lighting of at least 15% of the required illuminance. A few years later, a new standard PN-E-02030:1957 (PN-E 1957) was created. An intriguing point raised in the norms is the introduction of the required minimum illuminance in relation to incandescent bulbs and fluorescent lamps. In the introduction of the standard, it was stated that although with increased levels of illuminance the efficiency and quality of work increased, the cost of lighting and the load on the power plant simultaneously

[1] Currently referred to as illuminance, defined in lux [lx].

increased. Therefore, as a compromise, higher illuminance levels were recommended only when using fluorescent lamps due to their higher luminous efficiency.

The 1968 standard PN-E-02033:1968 (PN-E 1968), did away with the principle of normalising the lowest illuminance in favour of the lowest average illuminance. The illuminance advocated was the average illuminance related to the entire visual field. The next standard developed in 1984 by the Central Research and Development Centre POLAM in Warsaw PN-84/E-02033 (PN 1984) was adapted to the recommendations of the International Commission on Illumination (CIE) (CIE 1975). This document introduced a ranking of illuminance[2] and rules for the use of individual values. At the same time, depending on the circumstances, the obligation to increase or decrease the intensity level by one range in the adopted series was introduced. Additionally, for the first time, recommendations for colour temperature (CCT) and colour rendering index (CRI) depending on the illuminated space were introduced.

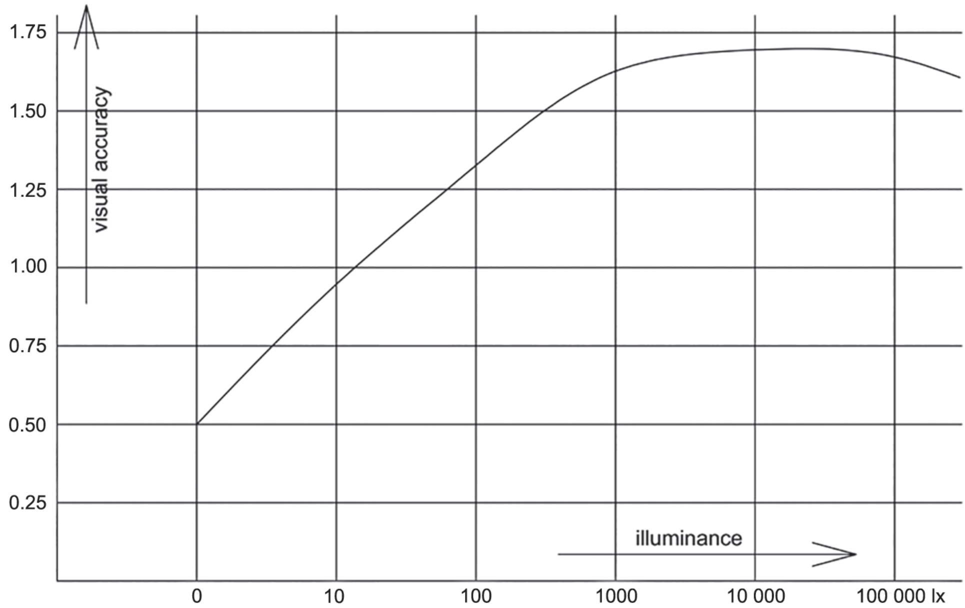
The 1986 standard was changed only in 2003, under PN-EN 12464-1:2003 (U)[3] (PN-EN 2003) – this was during a period of political change. The 2004 version (PN-EN 2004) is a direct translation PN-EN 12464-1:2003 into Polish, without any changes to its contents. This standard introduced new lighting design criteria such as light environment, visual performance and visual comfort. The intensity of illumination became related to the task and type of activity. It was emphasised that in the area of the room surrounding the task being performed (0.5 meters around the task "field"), a specific illuminance required for the immediate environment must be provided. At the same time, it was established that in interiors, the illuminance may not be less than 200 lx. It is also in this standard that the illuminance at the computer workstation was introduced at a minimum of 500 lx.

The new PN-EN 12464-1:2012 (PN-EN 2012) standard did away with the required minimum value of 200 lx in places for employees. In terms of "precision work", the required intensity level was determined at 750-1000 lx, with CRI = 90 and a colour temperature in the range of 4000-6500K, i.e. for the first time, several factors were combined to determine the optimal conditions of the workspace.

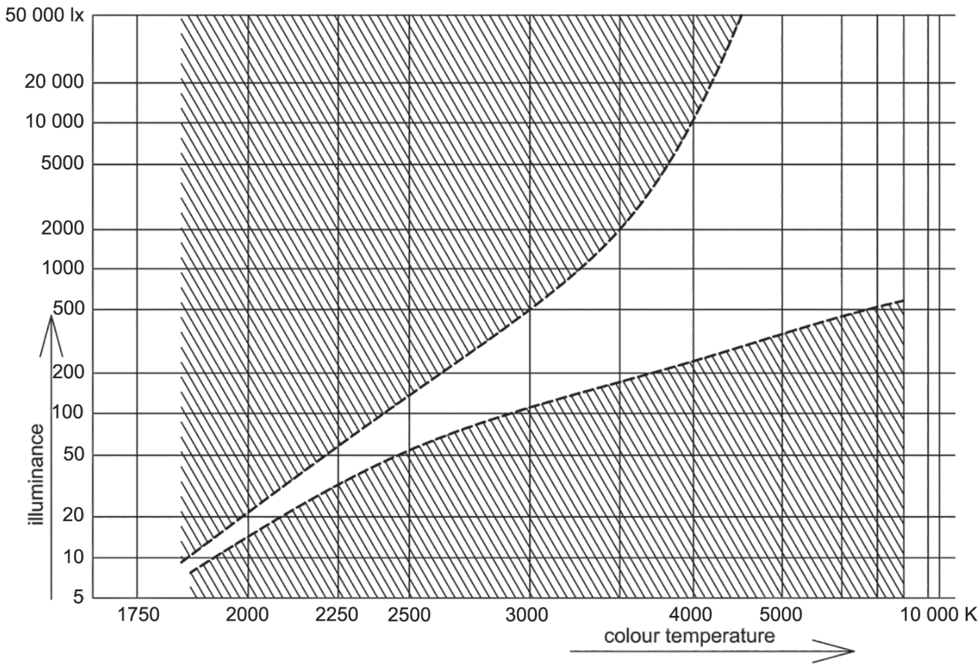
As one can see, the recommended illuminance values were successively increased. This tendency can be seen and compared in the two diagrams: the first by a Polish ophthalmologist, Władysław H. Melanowski, and the latter by a Danish physicist, Arie A. Kruithof.

[2] The following series of illuminance level thresholds is proposed: 10, 20, 50, 75, 100, 150, 200, 300, 500, 750, 1000, 2000, 3000, 5000 lx.

[3] The standard was introduced into Polish standardization by discretion, hence the designation (U).



Ill. 1.1. W.H. Melanowski's diagram showing the relationship between illuminance and visual accuracy. Ophthalmology Clinic 3/1935 (Author, after: Baran 1946, p. 16)



Ill. 1.2. Diagram by A.A. Kruithof showing the relationship between the colour temperature of the light source and the illuminance; Kruithof curve, original version (Author, after: Kruithof 1941, p. 69)

Melanowski's graph shows that the accuracy of perception increases substantially in the range from 1 to 5,000 lx. A further increase in illuminance no longer affects the accuracy of vision, and above 10,000 lx, this ability begins to decrease. The illuminance levels recommended by the standards do not exceed this level so far, but on the basis of Ill. 1.1, it can be seen that the level of demand for the amount of light is gradually increasing. This is not only due to the fact that the previously recommended levels were defined as minimal and the state's concern was to save on light, or in other words, to save on electricity.

The Kruithof diagram (Ill. 1.2) proposed in 1941 and developed on the basis of empirical research, describes what kind of light is considered to be pleasant by the recipients. In the graph shown in Ill. 1.2, this is a non-hatched area. This area shows what levels of illuminance should be applied to areas illuminated by light sources with a specific colour temperature (CCT). According to the figure, the cooler the light source, i.e. with a higher colour temperature, the higher the illuminance should be so that the recipients could perceive the space as pleasant. Various researchers did not fully confirm these observations, but it was found that a high level of colour temperature at low light intensity is unpleasant and that cool lighting is better received in combination with high illuminance (Vienot et al. 2009).

What could be inferred from this comparison? It should be noted that in modern life, our eyes are at all times, both day and night, bombarded by large amounts of artificial lighting, an amount of light that was unknown to our ancestors. Often, it is light for which the function is not to illuminate. People are surrounded by the world of screens: TVs, monitor screens, tablets, smartphones. Comparing these screens to light sources, they all offer cold light with a large range of blue waves, and this, according to the Kruithof curve, in order to be considered pleasant, should have a high luminance to produce the right intensity of illumination. The vicious "circle of dependence" is closed, the use of devices that trigger the need to use high levels of light intensity make us get used to increasing levels of light and only in such environments do we feel good. Humanity has become dependent on light, or more precisely, on high levels of luminance and illuminance.

One can wonder what else influenced this situation. The withdrawal of light bulbs from use has also undoubtedly contributed to this. For the past 140 years, mankind has functioned in the light of incandescent bulbs, the colour temperature of which has not exceeded 2800K. With this warm colour of light, a moderate level of illuminance was sufficient (considered acceptable and pleasant).

Striving for the ecological use of the resources on our planet – the sustainable use of energy has sparked a critical discussion of various topics related to the way humanity functions. The issue of round-the-clock access to light has also become a significant problem, especially since the light sources used were mostly better sources of heat than light. The solution to this issue was implemented in a radical way in the Directive of the European Parliament and of the Council of 6 July 2005 with the decision to phase out light bulbs[4] and replace them with energy-saving light sources (EC 2005). As a result of this action, bulbs of various strengths were gradually withdrawn from sale and from September 2018, halogen bulbs have also been phased out. Currently, only fluorescent lamps[5] and high-power light-emitting diodes in the form of individual sources and modules remain in use. All these sources have different radiation characteristics from both traditional incandescent sources and also from the same type of sources depending on the manufacturer's technology. Thus, seemingly similar products may have different optical radiation parameters (Pawlak 2015, p. 68).

The question could be posed of whether the spectral characteristics of fluorescent lamps and LEDs make it possible to replace traditional incandescent bulbs. The answer is a clear "no". These sources offer a new kind of light to which people have to get used to, just as they did to the new electric light in the nineteenth century. Energy efficiency – a slogan that eliminated the use of light bulbs – is often used with reference to fluorescent lamps, both linear and compact. However, it should be noted that while light bulbs and LED lamps are stored as part of ordinary electronic waste during their transfer and disposal, fluorescent lamps belong to the group of hazardous waste due to the mercury content (up to 5 mg in a unit). It can be questioned as to whether the envisaged energy savings sufficiently compensate for the cost of the production and disposal of fluorescent lamps.

Another factor to consider is the colour rendering index (CRI). In both cases, it is just over eighty, yet due to the complexity of the process of producing white light, it does not reach the maximum level of CRI = 100 of the traditional bulbs. LEDs are actually coloured lights with a narrow range of wavelengths, and it can be said that they are sources of monochromatic light. To achieve a wider light spectrum, the so-called hybrid method is used, i.e. inducing a yellow phosphor with blue light resulting in the impression of white light. In the case of fluorescent lamps, the parameters and properties of the light produced depend to the highest extent on the chemical composition of the phosphor. Generally, the visible radiation of these new lights – the traditional light bulb replacements – has inappropriate parameters and may have an adverse effect on health and the ability to work. At the same time, the amount of cold and blue light in the environment increases and affects human hormonal balance (Zawilska & Czarnecka 2006, Skwarło-Sońta 2015)[6].

[4] Due to the complexities of European law, this decision was taken without a vote in the European Parliament (Tabaka 2015, p. 13).

[5] One can still purchase "task bulbs", e.g. shockproof bulbs, which are "ordinary" tungsten bulbs sold under a different name in accordance with the 2005 directive. Such bulbs, according to the information on the packaging, are not suitable for domestic use.

[6] Light containing wave radiation in the blue range stimulates ipRGCs receptors on the retina, the so-called non-visual photic responses, which do not cause visual sensations, but may act negatively on the hormonal balance. Radiation in the range of 380-600 nm is responsible for the zircadine effects, especially at the level of the 460 nm wave (radiation in the blue colour range) (Zawilska & Czarnecka 2006). This phenomenon, combined with round-the-clock access to TV screens, monitors, laptops and mobile phones, becomes very phototoxic for the retina and generally dangerous to health (Pawlak 2015).

In reality, functioning and living in natural light is a variable as the light of the sunrise quickly changes from warm to cool. Around noon, sunlight has a very cold temperature, and in the afternoon, it begins to warm up again. In terms of the health aspect, the lighting surrounding us should function in exactly the same way, regardless of the functions performed during the day. Currently, artificial light in our day-to-day activities is never really adjusted in time in terms of colour temperature[7], and thus far, one can only regulate its illuminance by, for example, adjusting the number of light points, the power of light sources or the distance of lighting points from the illuminated planes.

Even today, in the countryside, the healthy principle of functioning between 5:30 am and 22:00 pm is adhered to, i.e. "getting up at dawn and hitting the hay when chickens do", resulting from the availability of natural light. Nowadays, we spend most of our lives with various forms of artificial light, whether studying, working, or even resting, whilst e.g. watching screens while unwinding in the evenings. This is because our habits have changed. We have been using task lighting increasingly often. In the last century, the basis for interior lighting was general light (chandelier in the middle of the room) and possibly a local light, e.g. at the desk, where homework was done, or a book was read. Currently, virtually every interior can boast of multi-point lighting, in which "zones" are created depending on the need. Multitasking in terms of lighting can be performed physically by using switches, but it has also become increasingly supported by various sensors and electrical devices controlled by remote controls or mobile phones. Added to this phenomenon is the zeitgeist of the present times: rapid change and the merging of many functions in one object, known as multifunctionality. Subsequently, with more lights being switched on, the levels of illuminance have been increasing as the sum of the intensities from individual points of light.

The issue of the demand for light has been picked up by the designers of residential buildings. The implementation of this trend for more light is happening in an intriguing way. In the development of top end apartments, we no longer deal with standard windows, instead we often see all external walls glazed. One can also notice less costly solutions with glazing mounted from a height of 45 cm above the floor to the lintel. Both of these solutions often render the interiors unusable in terms of good interior and furniture layouts. At the same time, the light effect to the exterior has the character of glazed office skyscrapers, where the light illuminates not only the interior, but also the immediate surroundings. The light of the "home", with increasingly higher levels of illuminance pouring outside, intensifies the light pollution in the city and contributes to increasing the level of average luminance in urban spaces. Campaigns and endeavours for the dark sky directed against excessive street lighting or strong illumination of specific objects are also destroyed by the light pouring out of offices, schools and, increasingly often, private apartments. Subconsciously or consciously, we have been polluting our outdoor spaces with light ourselves.

[7] Currently, installation of SMART lighting, i.e. lighting that can be adjusted not only in terms of not only illuminance but also the colour of light, is being recommended.

2. Urban lighting policies in practice: sustainability, light pollution and a night in the city – a comparative case study

Agata Łopuszyńska*

Attempts to shape specific outdoor lighting environments or limit their chaotic expansion in urban planning may not be a new topic but it is certainly not common (Narboni 2004, Brandi & Geissmar-Brandi 2007, Boyce 2014, Pothukuchi 2021). The comprehensive control of light pollution in particular has thus far failed to cover large swathes of cities. Satisfactory standards and methods for regulating light levels for urban areas have still not been developed (Narisada and Schreuder 2004, Perez Vega et al. 2021), and existing standards are considered outdated – often overstated (Mohar et al. 2017, Donatello et al. 2018, Skarżyński and Żagan 2020). Public awareness of the issue of light pollution is also low compared to other forms of environmental contamination (Youyuenyong 2015). Given the global increase in brightness (Sánchez de Miguel et al. 2021), the current state of the art and technology and the global energy crisis, the introduction of regulation in this sphere seems inevitable, although it is still being delayed. The state of peculiar abeyance between the conscious illumination and the machinic brightening of the night space poses a risk for low-quality realisations that may linger for years to come.

Developing a lighting policy that optimally balances the brightness in urban space after dark and the conditions of relative darkness in sensitive zones currently appears to be a major challenge. However, it can be argued that lighting is becoming a part of the increasingly conscious process of sustainable planning of urban areas (LUCI 2010, Davoudian 2019). The ongoing lighting modernisations to energy-efficient technologies is a stage of great opportunity to improve the quality of light and meet the goals of sustainable urban development. This work presents attempts to comprehensively implement lighting policies from the perspective of sustainable development and analyses their scale and scope.

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Sustainable lighting

The urban perspective on outdoor lighting places the human being at the centre but also takes into account the relationship with the surrounding environment. According to the sustainable development idea, each field of human activity must balance the social, economic and environmental spheres (Mensah 2019). The primary aim of sustainable lighting practices is to reduce the unwelcome phenomena generated by artificial light. In the urban space, several spheres can be singled out that can be negatively affected by excessive or inappropriate outdoor lighting:

- urban ecosystems (disruption of life cycles of living organisms, changes in the natural landscape);
- people (glare, effects on health, visual comfort and safety);
- landscape, in particular visibility of the night sky (sky glow, light "smog");
- energy infrastructure (transmission, energy consumption and energy efficiency of light sources);
- air and climate (carbon emissions associated with energy production and infrastructure).

Sustainable development in lighting is often considered solely through the lens of environmental or climate protection, including resource conservation. The term "light pollution" itself also has strong environmental connotations. However, these terms are often buzzwords[1] or used in so-called marketing greenwashing[2]. The problem, nonetheless, is more complex. Sustainable lighting is a much wider issue that simply energy efficiency, which is often referred to as green or eco technology. While it is a fact that we are globally striving to reduce energy consumption and carbon emissions, these criteria cannot determine whether lighting can be considered "sustainable".

It is also misleading to associate sustainable lighting only with the protection of dark skies, as it is not a primary need in a city in terms of light. On the other hand, in many countries, luminaires that minimise light pollution are often labelled as dark-sky friendly. However, more effective protection of dark skies is an obvious consequence of thoughtful use of lighting. The skies above cities will never be as dark as in uninhabited areas, due to the high accumulation of artificial light sources and applications. With evolving lighting techniques, however, it is possible to compromise between the requirements of sustainable lighting and the needs of an urban lifestyle.

[1] Words or phrases that have become fashionable as a result of frequent use, especially in the media and jargon. They are usually derived from technical terms, but their original meaning is changed over time as a result of popularization. In the field of urban planning, such phrases are, for example, smart, sustainable, resilient.

[2] Unwarranted green image creation and misleading by claiming the environmentally friendliness of a product or solution when this is not true, for material gain or to lobby a particular narrative favourable to the entity.

Objectives of the research

The main objective of the study was to identify contemporary international practices for reducing light pollution in urban settings, and thus regulations for real improvement in lighting quality in populated areas. Consequently, trends and motivations in sustainable lighting planning were also identified, problem areas were outlined and the benefits of practical methods for reducing light pollution were highlighted. For the purposes of the study, the author's definition of a sustainable lighting policy was outlined, which became the reference point for the qualitative analyses. With regard to paraphrasing the statutory definition of urban policy (Dz.U. 2021, 69), it was considered to be a set of legal, financial and planning measures for sustainable urban lighting aimed at exploiting the potential of light and improving the quality of life.

Methods

The comparative analyses presented in this study were developed after a detailed prior study of the cases, which allowed the processes and phenomena to be illustrated in the best possible way. The selected cases were first analysed in the contexts of law and spatial planning at the national level in a qualitative approach (Yin 2014), based on grounded theory (Charmaz 2009). The results of the comparative analysis (Rihoux & Ragin 2009, Whytock 2009) were presented in the form of overviews of common, pre-selected criteria. Theories were developed on the basis of qualitative data collected and analysed repeatedly. The comparative method made it possible to identify and present the diversity of contemporary solutions, their specificities and the mechanisms, dependencies and other factors behind them, which influence both the process and the enforceability of regulation.

The research is primarily cognitive, functional and pragmatic in nature. The analyses do not aim to inquire into the effectiveness of the presented ways of reducing light pollution, as there are currently no objective measures to assess such young policies and actions.

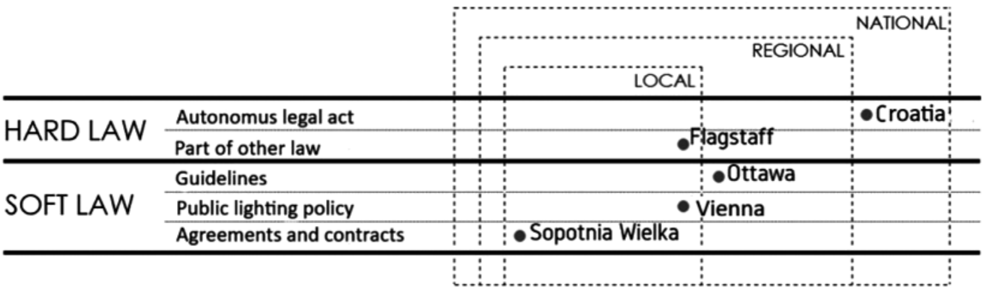
Case selection

As research material was acquired, it was possible to identify where actions aimed at light pollution abatement are being performed on almost every continent. The legislative context of the following countries (or parts thereof with independent legislation, e.g. states, cantons) was analysed: Mexico, Chile, Canada, United States, Australia, China, South Korea, India, Iran, Saudi Arabia, Finland, Norway, Belgium, the Netherlands, Germany, Scotland, England, Austria, Switzerland, Spain, France, Italy, Croatia, Slovenia, the Czech Republic and Poland. Some countries were excluded from further analysis due to limited access to source materials or language restrictions with too little available or with diversified literature. This was followed by the identification of detailed information on places, sites, initiatives or documents constituting lighting policies. Materials were primarily searched for and analysed in literature, databases, press, industry websites and even on social media.

As a result of the critical scrutiny, data on nearly forty cases of lighting policies and associated tools were obtained. For pre-selection purposes, this set of material was narrowed down to cases that:

- implement supranational sustainable lighting principles for reducing light pollution (recognised standards etc.);
- cover populated/urban areas;
- present spatially-comprehensive regulations (entire localities, regions, countries).

Two baseline selection criteria were ultimately decided upon: legal and spatial. With regard to the legal criterion, policies were divided into three ranks of the relationship towards light pollution: no regulation, soft law and hard law. With regard to the spatial aspect, it was considered qualitatively cognitive and interesting to divide the level of regulation from local to national actions, and the type of tools used for regulation from local infrastructure management to advanced policies. Based on this conceptual framework, five of the most extreme cases were selected, focusing on the cognitive purpose of the research (Ill. 2.1).



Ill. 2.1. Analysed areas of regulation in the context of lighting laws and policies. Source: own study

In order to keep the analysed content in order, consistent and comparable, several common quality parameters have been listed (Table 2.1). These indicators are divided into two sections that answer the basic questions of how lighting is regulated and what exactly the regulations cover. The state of the knowledge is current as of mid-2022.

Table 2.1. Framework and comparison criteria used in the case study. Source: own study

CRITERIA		GUIDING QUESTIONS
Method of regulation	Legal status of light pollution	Is light pollution defined by law? The relation of the law with intrusive lighting
	Territorial level	What territorial level does the regulation cover?
	Tools	What tools are used in the process of lighting modernisation?
	Legal force	Are the proposed regulations mandatory or voluntary?
	Spatial extent	To which spaces do the regulations apply: private or public?
	Timeframe, temporal scope	Do the regulations apply only to new investments or also to the replacement/revision of existing systems, e.g. lighting fixtures?
	Motivation for taking action	What are the motives behind the regulations? What spheres are impacted by the upgrades?
	Diagnostic measure	Were the regulatory actions preceded by analyses, studies, observations or measurements?
	Public participation in the process	Is the community involved in the regulation process and influential in shaping the changes? Is modernisation accompanied by activities to raise awareness of the issue?
	Standards used	What standards and patterns were used in setting guidelines and requirements?
Technical scope of regulation	Upward light emission	Is it prohibited to emit light above the horizon/upward? Are there exceptions to this rule?
	Shielding of light sources	Is protection against visual discomfort from glare applied? Is the light trespass limited?
	Light colour temperature	What is the recommended light colour and is it differentiated or conditioned?
	Zoning	Is there zoning of regulation in terms of its rigor or scope?
	Lighting operation time	Is the timing of lighting operation regulated? Is a time set for the luminaires to be shut off or dimmed? Are light control mechanisms used?
	Energy efficiency of luminaires	Are there energy efficiency requirements for luminaires?
	Energy/light amount limit	Are limits on the amount of energy or light adopted?
	Additional requirements	What additional aspects and considerations of light impact have been taken into account? Is there protection for brightness-sensitive areas such as residential areas, green and blue spaces?

Brief characteristics of the studied cases

Modernisation of outdoor lighting in Sopotnia Wielka, Poland (SO)

Conscious protection of the dark sky in the village of Sopotnia Wielka has been based on many years of grassroots work by a local association of amateur astronomers (later a non-governmental organisation) since the nineteen-nineties. Local activities, aimed at winning the favour of the authorities and the community, have turned into a driver for change in neighbouring municipalities. Sopotnia is now acting as a forerunner in light pollution awareness in the country through extensive popularisation activities and its own know-how. The small scale of the area has certainly facilitated the success of the regulatory efforts. However, it is emphasised that it is also a worldwide rarity to encourage lighting retrofitting for private individuals (Ill. 2.2). A comprehensive modernisation in the lighting infrastructure of the village was conducted and a commitment was obtained from the municipality of Jeleśnia to comply with the requirements for dark-sky-friendly lighting in public space (POLARIS-OPP 2021, 85-86).

Dark skies remain a priority for change, although the impact of light on humans is increasingly being taken into account. The activity in Sopotnia Wielka is not legally mandated and all its tools, including financial tools, originate from grassroots movements. Currently, the effectiveness of the regulation depends on the good will of authorities, investors and individuals. Without legitimacy, the future of dark-sky policy is uncertain, as no guarantees are in place for potentially harmful investments. Due to the lack of legislation on the issue of light pollution in Poland, efforts to obtain "International Dark Sky Community" International Dark-Sky Association (IDA) status are of great importance for the area.

Ill. 2.2. Modernisation of the architectural illumination of the church facade in Sopotnia Wielka in 2020, with the use of a contour light cut-off system. Source: https://ciemneniebo.pl/pl/dzialania-w-polsce/343-wymiana-oswietlenia-wokol-kosciola-w-sopotni-wielkiej

Zoning law of Flagstaff, Arizona, United States of America (FL)

Flagstaff aspires to be a model of a city that is developing spatially and economically while maintaining a high-quality lighting environment and reducing light pollution to a great extent. Flagstaff's profile is not typically metropolitan and a dark sky is treated as a valuable resource. The city has recognised that the region's atmospheric and topographical conditions are conducive to astronomical observations and, also for economic reasons, darkness protection has been made one of the directions of development. Long experience and scientific evidence have shown that regulations applied solely to the city area and its vicinity are insufficient, because the impact of the developing region, increasing in brightness, reaches tens of kilometres. The city therefore succeeded in "winning" darker skies for the whole of northern Arizona. The lighting code (Flagstaff City Code 2011), starting in 1973, has been successively updated and each time the regulations have been more restrictive and have covered more aspects (Portree 2002). Public lighting in Flagstaff is being modernised in accordance with dark sky protection requirements (Ill. 2.3), while private lighting is being subjected to rigorous restrictions. An important objective of this lighting policy is to develop and make globally available a way to modernise lighting to LED technology, in the most advanced way in terms of dark sky protection but also sustainability (Hall 2018a, Hall 2018b). The policy has involved many stakeholder groups at many levels and has developed tools specifically for this purpose. Technical, legal and organisational solutions have been developed, not hindering the development of the city and meeting the needs of different social groups.

Ill. 2.3. Test applications of amber-coloured LED street lighting in Flagstaff by Scott Johnson 2019. Source: https://arstechnica.com/science/2019/10/how-flagstaff-arizona-switched-to-leds-without-giving-astronomers-a-headache/

Urban lighting policy of Vienna, Austria (WI)

The Vienna lighting masterplan “Licht 2016” (Stadt Wien 2016) is a document that justifies and coordinates the city’s policy in the sphere of public space lighting and sets priorities in illumination. The multifaceted plan was made to specify requirements for lighting in terms of maintaining safety (including road safety), environmental protection, spatial composition of lighting, lighting technology and light pollution, and energy efficiency.

The masterplan focuses on street lighting and does not specify particular lighting parameters, leaving a margin for adjusting infrastructure to individual situations. The document is lacking in solutions for architectural illumination, and the only light colour temperature value adopted (4000 K) is described as a metropolitan standard, aimed at colour rendering and for crime prevention (e.g. the possibility of face recognition after dark). It cannot be said that this is a compromise solution for reducing the negative impacts of artificial light. The city’s private zone still remains unresolved. The city attempts to influence the choices of investors in terms of the unsanctioned prevention of nuisance and light pollution through indirect regulations of features such as road, commercial, building and advertising light sources, but most of these are difficult to enforce.

The lighting solutions included in the masterplan and implemented in public space are intended to provide a model for a sustainable approach to light and thus encourage positive change. However, the document provides a strong theoretical basis for sustainable lighting in an urban perspective, where human needs are put first. Vienna’s lighting policy makes a good example of trying to keep infrastructure up to date with the state of the art and new challenges of sustainable lighting (Ill. 2.4). The research-based approach to lighting is noteworthy as is the development of proprietary solutions independent of market trends and outdated standards. The lighting policy is also embedded in the city’s climate protection programs that have been underway since the nineteen-nineties.

Ill. 2.4. Street lighting of downtown Vienna after modernisation. Source: https://www.schreder.com/en/projects/customised-lighting-solution-help-vienna-achieve-smart-city-goals

Illumination Plan for the Ottawa-Gatineau Region, Canada (OT)

“The Capital Illumination Plan” (National Capital Commission 2017) is a concept that is compositional in nature, but supported by a substantive basis and motivation for undertaking lighting policy. The document contains a number of guidelines and recommendations, most of which relate to special areas for which the plan is legally binding (e.g. protected areas and objects, cultural heritage, national symbols belonging to the city, federal objects or resulting from the previously adopted road lighting policy). The vision also includes properties over which the metropolis has no authority to control lighting, but in this case, it is intended as a consensus tool and to encourage wider application of the recommendations.

The document is a successful attempt to find the golden mean in balancing the needs of lighting and preserving the darkness conditions of a highly urbanised and nationally strategic area. Some recommendations are not specific and leave a margin of discretion, which does not work in favour of implementation quality. Canadian law allows for local independent restrictions, but it seems difficult to reconcile the directions of development of various urban zones with equally different motivations for organising the night space of the city. The effectiveness of this lighting policy thus far has been the result of the various needs of the urban night landscape. Overall modernisation remains in the realm of the model lighting vision of the future.

Croatian law against light pollution (CH)

Croatian legislation relatively early on included light as a potential nuisance factor and defined light pollution (NN 2007); this entailed attempts to regulate it. Over time, lighting control began to be treated in an increasingly sustainable manner, not least due to the desire to keep up with EU climate goals for reducing the consumption of electricity. In practice, however, provisions turned out to be only theoretical, and delays in the development of implementing acts “froze” real changes. The breakthrough came in 2018, after the publication of a draft amendment to the law (VRH 2018), when Croatia was hailed as the country with the most progressive light pollution regulation in the world. However, a conflict of interest was externalised in the legislative process. On the one hand, the astronomy and environmentalist communities fought for protection against light pollution, while on the other, the lighting industry raised arguments about overly restrictive provisions and the lack of need for change. It came to pass that all the amendments submitted by the lighting industry were taken into account, and the law that was passed lost its original regulatory power. The amendments that resulted in allowing high limits for lighting undermined both the intent and the practical effect of the new policy (Ill. 2.5). The plan is to replace all lighting in the country to comply with the new law within twelve years – but ultimately, the installation of quality lighting remains dependent on the goodwill of authorities, investors and designers’ awareness of light pollution issues.

Ill. 2.5. Example of landscape lighting allowed by law on protection against light pollution, Lošinj Island by Boris Štromar 2015. Source: http://www.nasenebo.hr/?module=albums&page=viewalbum&album=2015%20-%20Otok%20Lo%C5%A1inj%20-%20%C4%8Cikat&pageback=kop13.php

Research findings: reviews and comparisons of lighting policies

Legal conditions

Of all the regulatory approaches examined, only Croatia has a legal, binding definition of light pollution (Table 2.2.). The first definition comes from the Environmental Protection Law, which depicts pollution as a change in natural brightness caused by human activity. In the Light Pollution Protection Act (in effect since 2011, with a 2019 amendment), the meaning of the term has been enriched to include information about the adverse effects of light used during the night on almost all aspects of life – from human health to landscape disturbance.

In Canada, pollution is not controlled at the national level, but local government regulations are binding. The term light pollution appears in regulations adopted for public roads and is used to describe the negative effects of artificial lighting.

The Flagstaff regulations operate on the basis of ambiguous definitions. This means that neither the law nor other regulations (e.g. planning documents) define light pollution but rely in a binding way on technical standards or guidelines that contain this definition. Hard documents, on the other hand, instead of light pollution, define the damage that light usage may result in. This is due to the legal system, based on the principle of limiting nuisances to real estate.

Table 2.2. Comparison of the legal definition of light pollution. Source: own study

Hard definition – statutory/legally binding definition	Croatia: “Light pollution is the change in the level of natural light at night, caused by the entry of man-made light” (NN 2007, art. 31(1)) “Light pollution is a change in the level of natural light at night caused by the emission of light from artificial light sources, which adversely affects human health and endangers traffic safety through glare and direct or indirect radiation of light toward the sky, disrupts the life and/or migration of birds, bats, insects and other animals and disturbs plant growth, threatens the natural balance, interferes with professional and/or amateur astronomical observations of the sky, and unnecessarily consumes energy and distorts the image of night-time landscape” (NN 2011, art. 2(1) pt. 1.)
	Ottawa, Canada: “Light pollution is a term used to describe the negative effects of the use of lighting such as light trespass, sky glow, and glare. With the proper use of light luminaires and pole heights, light pollution can be minimised. (…)” (City of Ottawa 2016, 43)
Soft definition – included in documents non-legally binding	Arizona, USA: “Any adverse effect of artificial light including, but not limited to, glare, light trespass, skyglow, energy waste, compromised safety and security, and impacts on the nocturnal environment” (IDA-IES 2011, 36)
Absence of definition	Austria: The term light pollution (German: Lichtverschmutzung) is not currently defined in law. An alternate definition – light immission (German: Lichtimmission) – is more common in soft law acts.
	Poland: The term light pollution does not appear in the legislation.

In Austria, equivalent to the term of pollution is the concept of light immission (German: Lichtimmission), which appears in the voluntary technical standard ÖNORM O 1052:2016 (ÖNORM O 2016), which can be translated as the harmful environmental impact caused by the emission and scattering of excessive light. The term light pollution itself is not defined in law.

In the case of Poland, there is no regulation, which is tantamount to the lack of a recognised definition of pollution. The only definition referring to the negative effects of light is found in the technical standard, referring to the lighting of outdoor workplaces as “an obtrusive light” (PN-EN 2014). The use of standards, however, remains voluntary.

Table 2.3 shows the spatial and temporal dimensions of the regulations as well as the obligatory provisions relating to them. In the case of Croatia, in practice, the binding provisions are combined with significant exemptions because, as mentioned above, the enacted law, incorporating almost all of the amendments proposed during the consultation process, has softened the originally intended rigor. Limitless lighting is still possible in many situations.

Table 2.3. Scope and scale of regulation: spatial and temporal dimensions, obligatoriness (the grey scale used in the table is only for better differentiation of individual columns). Source: own study

				SO	WI	FL	OT	CH
	Population			2 thou.	1.9 mil.	60 thou.	1.3 mil.	4.1 mil.
REGULATION	Spatial scale	Local						
		Regional						
		National						
	Obligatoriness	Binding	Public space	*				*
			Private space					*
		Voluntary						
	Timeframe of applicability	New realisations + alternations				*		
		Existing			*			

* subject to certain limitations

Local regulations in Flagstaff have had a major impact on the region, leading to a spatial expansion of the influence of policy over county and state regulations. Regulations apply to both the private and public spheres, but greater rigor applies to public lighting. Implementation of the regulations is based on the issuance of permits or orders to shut down during certain hours if private lighting does not meet current requirements.

In Vienna, only existing lighting in public spaces is mandatorily replaced, and new public developments are brought into compliance in accordance with the lighting policy. In the private sphere, lighting retrofits are ordered only in cases of identified negative traffic impacts.

Ottawa does not have long-term plans to replace all lighting in the public realm. Implementation of the policy is based on planning activities contained in the master plan, which, inter alia, singled out priority areas for illumination intervention.

In Sopotnia Wielka, all activities are based on non-legally binding agreements and policy built over many years with public consent. Only recently has an agreement signed with the municipality been in place, binding the parties to adhere to the practice of dark sky protection in public space, despite the lack of legal regulations.

Sopotnia's lighting policy is bottom-up and soft in nature (Table 2.4). Recommendations in relation to lighting are based on a system of measures derived from IDA recommendations and have no legal force. In Croatia, the Light Pollution Law makes an elaboration of the light protection regulations previously established by the Environmental Protection Law. The law is supplemented by an implementing document in the form of an ordinance, in which regulations are based on established normative indicators and zoning. However, the adopted normative benchmarks and the scope of possible exemptions from them are controversial.

Table 2.4. Type of legal regulation and light pollution assessment system (the grey scale used in the table is only for better differentiation of individual columns). Source: own study

			SO	WI	FL	OT	CH
LAW	Hard	Autonomous legal act					
		Part of other law				*	
	Soft						
POLLUTION ASSESSMENT SYSTEM	Based on metric system		*				
	Subjective evaluation of nuisance						

* subject to certain limitations

The other analysed lighting policies are based on subjective (locally interpreted) concepts for assessing nuisances from light. In Flagstaff, such a concept includes a locally applicable system of indicators in the form of a limit value for a unit of light per property area (lumens per acre). The masterplans for Vienna and Ottawa are recommendatory and coordinate other operations in the city's public policy sphere, including climate change prevention, safety or a visual image.

Regulation process: motives and tools

An interesting issue in the comparative analysis is the motives behind the adopted lighting policies and the priority areas for their implementation (Table 2.5). Common motivations identified in the regulatory processes are energy efficiency, safety in space, and the impact of light on human health and the environment.

In Flagstaff, the initiating impulse was issues relating to the preservation of dark skies. Very quickly, however, it was backed up by budgetary arguments, as serious financial resources began to be invested in astronomical equipment (including military). A strong premise was the improvement of safety in the night space, understood here mainly as the protection of property from unwanted light and the protection of health, visual comfort and the safety of pedestrians in traffic. Aesthetic considerations were also raised.

In Vienna, in addition to motivations related to energy efficiency and dark sky protection, the dominant rationale was to ensure a good visibility in the space after dark. The Austrian capital was the only one to motivate lighting strategies with the equality policies (City of Vienna, n.d.).

In Ottawa, lighting policy is part of the capital region's development strategy, including image enhancement and identity construction. No mention is made of the cost or impact of lighting on climate change. Dark skies are not a priority either, rather the protection of ecosystems coexisting with the metropolitan tissue.

Table 2.5. Motivations for adopting sustainable lighting practices (the grey scale used in the table is only for better differentiation of individual columns). Source: own study

	SO	WI	FL	OT	CH
Natural environment					*
Climate					*
Economy, budget	P				P*
Energy savings		P			P*
Safety/security		P	*		
Health		*			*
Visual comfort					
Aesthetics of space					
Illumination composition				I, P	
Landscape conservation					
Development strategy	P	*	P	P	
Gender mainstreaming					
Dark sky protection	I, P	P	I		*
Astrotourism					

I – initial motivation; P – priority
* – with limitations, if inconsistencies in legislation or enforcement are found

In the case of Croatia, on the other hand, the initial motivation for adopting regulations was several aspects at once, but the legal provisions that were developed precluded their implementation in practice. The prioritisation of energy efficiency here has a textbook rebound effect – the law allows an increasing number of energy-efficient lamps.

In Sopotnia Wielka, the priority and initial motivation of the lighting policy was the protection of the dark sky, but issues of minimising budget expenditures all the time remained the main goal of the local governments involved. The protection of the landscape is understood in this case as the preservation of natural darkness rather than the conditions of nocturnal spatial order.

Table 2.6 provides a summary of the most important and supporting regulatory tools used in the process of light management. The least number of instruments was identified in Croatian legislation, where they are limited to a formal minimum or mandate local governments to manage the process of creating plans and implementations required by law. The richest and most diverse tools were developed by the lighting policies of Vienna and Flagstaff.

Vienna's masterplan coordinates an extensive lighting policy that has been implemented for a long time. The city encourages changes in the lighting environment through model actions in public spaces. Also noteworthy are the diverse educational publications, from school publications to tender documents. The city stands out for constructing its own high-quality lighting solutions and sharing them.

In Ottawa, the document was created to plan and standardise the city's night-time image. However, there is a lack of coordination of the masterplan's implementation system at the regional level, while there are plans to develop a commitment charter document.

Table 2.6. Key tools used in the lighting regulation process. Source: own study

	Main tools	Complementary tools
Sopotnia Wielka	Non-legally binding contracts and agreements	• local strategic documents • popularisation activities • independent financing strategy • community activisation
Vienna	Lighting masterplan to coordinate the current urban policy	• insightful diagnosis of the lighting environment • media action: public space as an exemplary model of lighting • a set of recommendations adjusted to urban conditions • Vienna lighting catalogue • community education and know-how
Flagstaff	Zoning code coordinated with the city's general plan	• linkage to regional and higher-level strategies • urban policy monitoring • enforcement instruments • diversification of financing • local government consulting, know-how, popularisation • public participation
Ottawa	Compositional master plan based on public space regulations	• media action: public space lighting as a showcase of the region • a set of guidelines for metropolitan needs • educational and participatory activities • reporting on ongoing modernisations
Croatia	Law and implementing orders	• public display and consultation of draft legislation • delegation of implementation and enforcement responsibilities to the local level

In Flagstaff, the zoning code is coordinated with the city's master plan, county (Coconino County 2022) and the state laws (ARS 2021), which legally secures the policy profile. In addition, there is a document that tracks plans for the development of observatories, military and Navajo Reservation lands and examines the impacts of implemented territorial policies (Coconino County 2019). The city aspires to take a leadership role in dark sky protection in urban areas, so it is eager to share its know-how with other local governments.

In Sopotnia, the main axis of activities is popularisation, without which, it would not have been possible to develop the grassroots lighting policy to such an extent. Also noteworthy are the successive development of the light pollution thread in strategic documents and the financing plan, which is largely independent of local authorities.

A significant element of modern planning and legal processes is public participation (Table 2.7). Sopotnia Wielka's policy is undeniably based on a grassroots movement, so it is formed from the ground up by a growing social movement. An important component of the activities is community activation and nationwide popularisation activities. A similar approach is seen in Flagstaff, where public participation is a natural part of all changes in the lighting environment. All ventures are transparent, and cross-sector cooperation gives a greater sense of compromise.

In Vienna, the city's administration supports the development of grassroots ideas that fit into the chosen policies, such as light measurements. Feedback on implemented projects is gathered through an online platform and during site visits, but more policy influence comes from the work of experts and support in the research.

In Ottawa, the community has a say in, among other things, prioritising city facilities for illumination (Ill. 2.6). However, these actions are based more on subjective perceptions of the night-time city than on rationales supporting spatial order at night.

Table 2.7. Public participation in lighting regulation processes. Source: own study

Citizen participation	
Sopotnia Wielka	• involvement of NGOs • public consultation of documents, workshops, festivals, demonstrations, community activation • supporting the proper choices for private lighting
Vienna	• real openness to civic and scientific initiatives • gathering opinions on projects
Flagstaff	• surveys, obtaining residents' feedback on planned changes, educational seminars • intersectoral cooperation, including with organisations • public consultations: open committee meetings, open online platform for urban planners • night tours of the city, educational workshops, conferences, free light bulbs of the appropriate spectrum/colour temperature
Ottawa	• public consultations, discussions, online surveys • educational workshops, city walks with residents
Croatia	• statutory obligation to make public access to information on so-called lighting plans and action plans for the installation and modernisation of lighting • public consultations, public participation in working groups

Croatian law requires that access to information about lighting plans or tenders be made public. Citizen consultations are more formal and their outcome is hardly conclusive for the authorities. Conflicts of interest in agreeing on draft legislation remain unresolved.

Ill. 2.6. An exploratory night walk organised by the National Capital Commission to engage residents in developing the Capital Illumination Plan. Source: https://www.arcgis.com/home/item.html?id=1575d471e658431d9bbd3e9d0a79dbac

Actions in response to the issue of dark sky protection are more supported by scientific research and rationally justified than the other motives (Table 2.8). In Sopotnia and Flagstaff, measurements and comparisons in night sky brightness are linked to IDA certification requirements. In Flagstaff, studies of city space lighting are used to analyse the relationship between dark sky policy and land use. As in Vienna, new luminaires are tested in the space and reviewed by residents. In the Austrian capital, lighting is also being inventoried and studied, but it is not the protection of the night sky but people who are the main subjects. In addition, the city's brightness monitoring is linked to the control of air quality.

Table 2.8. Diagnostic activities accompanying the process of regulation with scientific background. Source: own study

Analytical and diagnostic actions	
Complete	
Vienna	Flagstaff
• Long-term and comprehensive brightness and pollution measurements: aerial and manual (combined with monitoring of the air condition) • Lighting inventory and assessment • Luminaire lighting laboratory, facades testing for light trespass or effects on insects • Test lighting in city space	• Tests of lighting in the city space and the laboratory, gathering feedback • Brightness measurements; research on the effect of land use and regulation on changes in artificial brightness • Lighting inventory and research in city space • Scientific conferences, expert consultations

Table 2.8 (cont.)

Selective	
Sopotnia Wielka	Ottawa
• Brightness measurements, collecting of comparison images • Following the IDA guidelines • Organisation of scientific interdisciplinary conferences	• Observation and perceptual analysis of lighting in space • Studying international good practices • Expert groups
Discretionary	
Croatia	
• The use of the opinions of working groups composed of: experts, activists, entrepreneurs, politicians	

The diagnostic efforts in Sopotnia Wielka and Ottawa are not so comprehensive and correspond to the chosen directions for shaping the local lighting policy. In Sopotnia, they are subordinated to the protection of dark skies, while in Ottawa, to the creation of a nocturnal image of the capital region.

Despite the fact that Croatian legislation includes protection against pollution on a nationwide scale, no brightness monitoring or research on lighting urbanism was found there. This is handled independently by volunteers and dark sky activists.

Another issue of research interest is the specially established institutions and positions to support the implementation of the chosen lighting policy (Table 2.9). This issue is most developed in the case of Flagstaff. The city administration, in the sphere of assessing compliance with local zoning codes, has created a position dedicated exclusively to lighting control (code compliance officer). He investigates reported complaints and violations, assists contractors and designers in selecting luminaires and evaluates outdoor lighting permit applications. He is also in charge of patrolling the city after dark, checking for blatant violations of the law. The city's dark sky committee, appointed to implement the city's lighting policy, collaborates on updates to the city's code, such as in the realm of new lighting technologies. The city also uses a spectrometer with which another specialist (a dark sky compliance specialist) inspects the colour temperature of private luminaires. He also creates lists of places where lighting is not yet up to existing standards.

Table 2.9. Established special institutions and positions related to lighting regulation. Source: own study

Sopotnia Wielka	–
Vienna	Department of the municipal office Environmental protection advocate
Flagstaff	City positions to control lighting and inventory of illegal lighting Dark sky committee at city council City zoning code administrator

Ottawa	–
Croatia	Project working groups involving organisations and experts Accredited individuals to measure lighting State-licensed installers as a condition of permit issuance Lighting operators as responsible for the process

In Vienna, a department of the municipal authority responsible for public lighting (MA33) has been established with about 150 employees. Municipal policy is also supported by the institution of an independent environmental advocate, which acts as a coordinator of activities over light pollution. In the case of lighting, the city also cooperates with the city's urban planners and architects and uses external consulting services in the sphere of technological solutions. Legal control of lighting emerges from separate regulations and is conducted as part of the daily work of environmental, construction or trade inspections.

In Croatia, the working groups set up to project lighting acts have different memberships (and thus represent a different balance of power), from politicians, astronomical organisations to lighting industry designers. New conditions also result from the new legislation, as in the case of a lighting permit, where a state-licensed installer is required, or accreditations for lighting measurements. Local governments are required to enforce the regulations and enact smaller lighting plans, and the environmental inspectorate and the head of the municipality are authorised to inspect compliance of implementation with the law.

In the case of Ottawa, master plan considerations are handled by regional urban planners (National Capital Commission) on an equal footing with other responsibilities. However, they benefit from the cooperation of external experts and consultants.

As part of the work of non-governmental organisations operating in Sopotnia, there are internal groups assigned for specific purposes, which also usually have diverse sources of funding. A great support of their activities is certainly the work of volunteers. However, the program envisages the establishment in the future, in consultation with the village and municipality, of a "dark sky guardian" position – to report on improper lighting and to negotiate and assist with funding in the case of possible lighting upgrades.

Technical solutions

Places that prioritise the protection of dark skies base their activities on the standards of the IDA organisation (Table 2.10). This is primarily the "Model Lighting Ordinance" (IDA-IES 2011), as in the case of Sopotnia Wielka. In Flagstaff, researchers have proven that more effective than these guidelines, is an earlier version of the "Pattern Outdoor Lighting Code" (Luginbuhl 2010), which they also include in the zoning code. The recommendations in both cases must comply with national standards: in the United States, the IES, and in Poland, the PN-EN. In the agreement between the dark sky organisation of Sopotnia and the municipality, it is recommended to use the norm, which in addition to providing for minimum values for lighting parameters for sports facilities is also advanced in terms of recommendations for reducing light trespass, glare and upwards emission (PN-EN 2019).

Table 2.10. Norms and guidelines used in the analysed policies. Source: own study

Guidelines developed by organisations	IDA (international)	Flagstaff: Pattern Outdoor Lighting Code, Model Lighting Ordinance Sopotnia Wielka
	RASC (Canadian)	Ottawa
Standardisation	National norms	Flagstaff: adapting dark sky requirements to IESNA standardisation Ottawa: ANSI/IESNA, TAC Vienna: ÖNORM O 1052: 2016 06 01 (adapted to EN13201)
	European Norms EN	Vienna: European norms adapted locally to national specificities Croatia: operating on European and British standards, including BS EN 13201 Sopotnia Wielka: recommendations to use CSN EN 12193
Other recommendations	International	Vienna: references to CIE: 150:2010

Standards adopted in Vienna are also aligned with European norms, but Austria has established its own additional technical norm for measuring and assessing light pollution – ÖNORM O 1052. This, in turn, provides values for maximum permissible light thresholds, unlike the classic European standards, but the current legal system prevents their widespread enforcement. Vienna emphasises the need for local adjustment of light parameters through the work of urban planners and light technicians.

Croatia, despite having theoretical strict protection, relies mainly on European road standards and their British counterparts, where only minimum levels for light are set.

Ottawa's illumination plan does not point to specific standards, but it is in line with binding policies in its area, such as public roadway lighting, which is defined by an American standard (IES 2014) and a Canadian transportation standard (TAC 2006); however, it is important to mention the source of the approach to light pollution, which originated in the activities of RASC (Royal Astronomical Society of Canada). In Ottawa, the publication of the illumination plan was preceded by studies of international best practices, but it is difficult to identify all the model standards used.

Table 2.11. Scope of technical requirements for lighting regulations. Source: own study

	SO	WI	FL	OT	CH
No upward light emission					*
Prevention of light trespass					
Colour temperature of light		*	*		*
Environmental zoning of brightness					*
Operation time of the lighting					*
Energy efficiency of luminaires					*
Energy/light amount limitation					
Protection of sensitive areas					*
Solutions for architectural illumination			*	*	
Glare protection					
Lifespan and maintenance of lamps					

* partly/with substantial exceptions

Table 2.11 shows the full range of technical requirements recognised in sustainable lighting practices in the cases studied. In the case of Sopotnia Wielka, due to the legal situation and the small scale and homogeneity of the area, there is no zoning. Lighting modernisation took place in the years when LED technology was not yet widespread, and the energy savings come mainly from the proper targeting of light, the illuminance values and the control system.

Regulations in Vienna have been guided by subjective assessments, without suggesting specific indicators, such as the colour of light, except for one specification for street lighting. The lack of environmental zoning is related to the adopted road lighting class system. The protection of sensitive areas, on the other hand, is coordinated with other city policies, such as planning and the protection of special zones, such as greenery.

In Flagstaff, acceptable colour temperature is related to limiting the contribution of blue light more than the actual effect of light colour. Because of the strictly forbidden upward direction of light, specific solutions have been defined for illuminating buildings, but these are not typically decorative, but more utilitarian, such as illuminating canopies, gas stations, and signs.

The zoning of brightness in Ottawa is more compositional in nature, but carefully tailored to the spatial structure of the capital area. Limiting the intrusion of light from architectural illuminations into the surroundings is recommended, but specific technical solutions are not indicated.

In Croatia's national lighting policy, the number and nature of exemptions from the lighting requirements indicated in the law are so large that it is difficult to categorise them. The law is only effective if there is goodwill among the parties involved in the lighting process.

Conclusions

The cases presented above show diverse approaches to lighting regulation, but it is possible to systematise the governing mechanisms, motivations or solutions. The spatial scope of lighting policy certainly affects the comprehensiveness of solutions and the obligatory nature of regulation. Smaller areas are easier to control, while larger ones reflect the result of different kinds of interests and conflicts, that are difficult to reconcile. The legal definition of light pollution is not a prerequisite for the effective enforcement of lighting policy, nor does it set a limit on the legality of implemented solutions. In some circumstances, categories of the effects of its negative impacts are more often defined than light pollution itself – the characterisation of the impacts is already a factor facilitating the reduction of the adverse effects of lighting.

Globally, lighting regulation is heavily influenced by overarching federal or EU policies, inter alia, in the area of electricity management. In Europe, less autonomy in local regulation is noticeable. Only Austria has introduced its own technical standard, albeit coordinated with EU standards. In the United States and Canada, there are more opportunities for legal nuisance abatement, but the nature of regulation depends on local developments, especially economic developments. Lighting regulation is usually a part of other policies and agendas, and rarely makes autonomous legislative and planning structures.

Lighting policy still has the most force over public space, unless light nuisance is controlled by law, and keeping light within desirable limits is considered a safety factor. This also involves how nuisance is assessed and how measurable it is. In places where protection of private property is more important, limiting the impact of light is more socially acceptable and enforceable. In most cases, however, private lighting replacement remains voluntary.

Dark-sky protection and astronomical motives often initiate changes in the approach to lighting control, but energy efficiency and budget remain the main motivations for regulation. More often, lighting policy is also becoming part of development strategies, but in conjunction with economic or image goals. Night-time spatial order is not currently a stand-alone goal of lighting ordering in urban areas, although such attempts are being made, mainly by metropolitan centres.

The most common obstacles to using lighting of "healthy" parameters are aesthetic and vehicular traffic regulation issues. In both cases, the use of "warm" light colours is avoided. There is a clear problem with lighting standards, as most of them are based on technical norms relating to road safety. In addition, they are mostly applied voluntarily, and often discretionarily and selectively. These standards do not keep up with environmental changes or lighting technology. Technical road norms aim to provide visibility conditions that are close to daylight, so they are based on minimum light performance indicators. This is in contrast to a sustainable approach. The concepts of subjective assessment of nuisance are mostly ineffective and difficult to enforce, so they are often extended by the introduction of metrics as a determinant of acceptable light intrusion.

A great strength in lighting policy is its grounding in scientific, comparative research and the testing of solutions preceding investments in space. This is linked to greater awareness of the consequences of actions taken and the effects of its impact on space and user groups. The lack of a solid scientific basis can result in weaker coordination of activities, inconsistency, often superficial rationale or following marketing trends to the detriment of the quality of implementation.

Certainly, one may already speak of a lighting policy in urban areas. Actions in this regard are becoming increasingly sustainable and comprehensive. There is a growing awareness of the consequences of light pollution, as well as the sheer importance of artificial brightness in the city. The biggest obstacle to regulating light at the local level is unfavourable and unresponsive legislation. Another complication is the requirements of other sectoral policies and regulations that conflict with sustainable lighting. Other issues worth noting include the direct correlation of safety in spaces with lighting levels, public reluctance to change in brightness (especially to reduce it), and the presence of lighting industry lobbies in association with imperfect public local government policies.

While there are international models for implementing dark sky protection, there is a lack of good solutions for sustainable lighting of urban space with more diverse structure and a profile of needs and constraints. There are already changes on the horizon, but they are not yet systematised. Currently, reducing light pollution in the city mostly involves years of trial and error. Good practices are expected to become more widespread over time, but the direction of lighting policy development is still subject to global fluctuations.

3. Light pollution as a possible factor disturbing balanced bat-virus relationships

Krystyna Skwarło-Sońta*
Krystyna Zużewicz**

Life on earth in the twenty-first century is inseparable from the global urbanisation progressing every year, which is obviously responsible for numerous changes in the natural environment. Landscape change, deforestation, as well as the loss or fragmentation of the habitat of numerous animal species are the main effects of urban expansion and development (Egert-Berg et al. 2021). So far, little has been said about light pollution in this context, although city lights are among its main sources.

There are several definitions of light pollution, mainly directed at the physical and ecological aspects of this phenomenon (Cinzano et al. 2000, Longcore and Rich 2004). One of the definitions joins both presented points of view by calling light pollution "any change in the natural lighting caused by the introduction of artificial light, especially when it is scattered above the ground level and negatively interferes with the functioning of living organisms" (Patriarca & Debernardi 2010). The presence of artificial light at night (ALAN) influences animal behaviour by modifying their orientation ability and species distribution (Polak et al. 2011), but it also acts as one of the strongest disruptors of the circadian system, mainly by the inhibition of melatonin synthesis in the pineal glands of vertebrates (Hardeland 2014). Light pollution affects the species with both nocturnal and diurnal patterns of activity, although the mechanisms involved vary widely (Dominoni & Nelson 2018).

Bats – very special nocturnal mammals

There are about 1,400 bat (Chiroptera) species worldwide and they are among the most numerous orders of mammals. Bats can be divided into three trophic groups: herbivorous, insectivorous and vampires (those that feed on the blood of other animals). Depending on their diet, bats play important, though varied, roles in the ecosystem, which can be summarised as follows:

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- Bats pollinate plants including economically important cacao and banana trees as well as agaves.
- They spread seeds of the rainforest.
- They provide guano used as a fertilizer.
- They reduce populations of insects which spread disease (e.g. mosquitoes) and decimate harvests.
- They kill insects which are believed by many people to be intrusive.

Being nocturnal, small-sized social mammals with a unique ability of powered flight, bats still represent a mysterious group of animals of which the physiology is not fully understood, and therefore they are frequent objects of both admiration and persecution (Rocha et al. 2021).

Due to the anthropogenic pression, a huge decline in bat population was noted during the last century, which is estimated to be an approximately 70% loss in Europe (Gunell et al. 2012). Nocturnal activity makes them especially vulnerable to the effect of ALAN (Patriarca & Debernardi 2010), as most bats leave their habitats and forage at night while the additional lighting disturbs their hunting (especially as far as insectivorous species are concerned), roosting and commuting (Gunell et al. 2012). This problem will be discussed in detail in the next sections.

Poland is inhabited by twenty-seven species of bats, and the majority of them belong to *Rhinolophidae* and *Vespertilionidae* families. All the bat species that live in Poland are subject to strict legal protection that particularly concerns those listed on the IUCN (International Union for Conservation of Nature) Red List of Threatened Species. According to EU law, there are areas designated for seven bat species – Nature 2000 – including their colonies and feeding grounds. These species include: lesser horseshoe bat (*Rhinolophus hipposideros*), greater horseshoe bat (*Rhinolophus ferrumequinum*), Bechstein"s bat (*Myotis bechsteinii*), pond bat (*Myotis dasycneme*), greater mouse-eared bat (*Myotis myotis*), Geoffroy's bat (*Myotis emarginatus*), and barbastella (*Barbastella barbastellus*) (Bat species in Poland 2012).

Bat immunity

The defence of mammals against pathogens is possible thanks to the specialised processes of innate and adaptive immunity. Fundamentally, the bat's immune system is no different from that of humans and mice, both at the level of immune organs and immunocompetent cells, including the white blood cell (WBC) count. The adaptive immune response in bats (both cell-mediated and humoral immunity) is somewhat delayed and weaker than in mice, while a notable difference between bats and terrestrial mammals is in the lack of certain genes encoding the recognition of microbial DNA; therefore, bats seem to be less sensitive to such infections (Beltz 2018). However, it must be emphasised that due to the huge number of species, some immune parameters may show considerable variability within the order of Chiroptera, thus general conclusions should be drawn with the greatest caution (Subudhi et al. 2019).

Adaptive immunity is a sequence of energy-consuming processes involved in the trade-off with other essential activities, which in bats, as compared to other (terrestrial) mammals, need particularly large amounts of energy. These activities include powered flying, reproduction (especially in females) and exceptional longevity, which not only distinguishes bats from mammals of comparable size but is also greater than that of birds which, like bats, are less vulnerable to attacks by terrestrial predators (Mandl et al. 2018). On the other hand, innate immunity not only requires lower energy expenditure than adaptive immunity but also develops more rapidly. Therefore, the innate immunity of bats is their first line of defence. It is activated mainly by interferons (IFNs), a group of cytokines responsible for inhibiting the replication of viruses that have infected an individual (Beltz 2018).

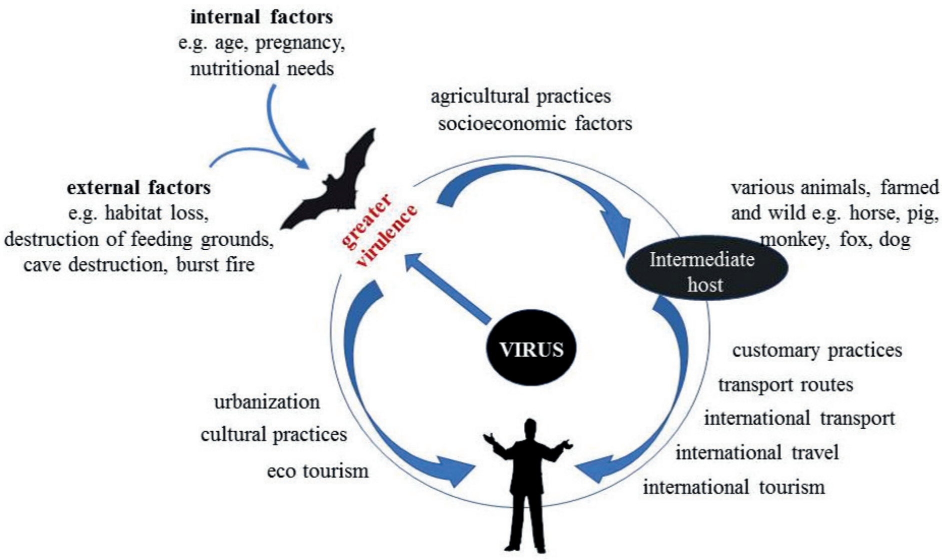
The induction of IFN starts after the recognition of so-called pathogen-associated molecular patterns (PAMPs), structures derived from various pathogens and absent in the uninfected host cells. A detected infection activates the intracellular signalling cascades ultimately resulting in the inhibition of virus replication and the development of a pro-inflammatory response (Barenjee et al. 2020, Clayton & Munir 2020). However, bats have evolved an ability to limit virus-induced pro-inflammatory response together with limited virus replication as a result of the active expression of antiviral genes, i.e. IFNs and IFN-stimulated genes (ISGs), constituting molecular equipment interpreted as an "always ON" IFN strategy or an efficient antiviral ISG defence (Subudhi et al. 2019). However, in some circumstances, the host immunity is suppressed, and the virus replication increases leading to the active shedding of viruses (see later). An advanced description of the molecular basis of bat immunity and its regulation exceeds the scope of this study. Therefore, we only want to briefly quote the latest results obtained in studies on the Jamaican fruit bat (David et al. 2022), in which an experimental infection with various RNA viruses resulted neither in important viral replication nor visible symptoms of disease.

Ability of the energy-costly powered flying has evolved in bats simultaneously with an active suppression of inflammation, which in other animals rises along with an increased metabolic rate generating pro-inflammatory free radicals. Although these physiological traits create the convenient conditions for virus replication, in bats it is balanced by more effective antiviral activities, i.e. the elevated expression of IFNs and ISGs. These evolutionary adaptations enable explaining bats' functioning as the viral hosts with asymptomatic infections. Additionally, due to the huge number of individuals in one bat population, virus replication and clearing from infected individuals is a continuing process allowing the infection to be spread to the new, naïve individuals and maintaining the relatively high level of the viruses in the population. Therefore, bats are considered to be reservoirs of human viral pathogens (source of zoonotic diseases) (Mandl et al. 2018).

Bats as reservoir hosts of zoonotic diseases

Bats are considered to be one of the most significant sources of zoonotic (animal-transmitted) diseases. They are often infected with more viruses per species than even rodents, although the number of rodent species exceeds that of bats (Luis et al. 2013). Bats live in clusters of thousands and millions of specimens, which promotes the multiplication of infecting pathogens. Moreover, due to their ability of powered flying, they can cover hundreds of kilometres in one night and seasonally they migrate over thousands of kilometres, fostering the spread of infection. Bats are reported as natural reservoirs of several viruses, many of which are highly pathogenic to humans while persistently infected bats usually do not show any clinical symptoms of illness.

Molecular studies indicate that bats are natural reservoirs of such viruses as: filoviridae, e.g. Marburg, Ebola (Briand et al. 2014); paramyxoviruses, e.g. Hendra, Nipah (Smith & Wang 2013, Looi and Chua 2007); coronaviruses such as SARS or MERS (Wang et al. 2006, Mohd et al. 2016). All the aforementioned viruses are RNA viruses, which, adapting their survival to the host (bat), tend to mutate faster. To prevent diseases, bats must detect and eliminate pathogens while viruses have to maintain replication and transmission above extinction threshold (Real & Biek 2007). Under conditions of weakened host immunity (or when the virus can overcome its effectiveness), virus replication becomes more efficient and results in virus excretion. The route of shedding (i.e. in saliva, urine or faeces) largely depends on the organ of the particular intensity of multiplication of viruses, i.e. the gastrointestinal tract or kidneys (Subhudi et al. 2019).



Ill. 3.1. Factors favouring the shedding of viruses hosted in bats (based on Smith & Wang 2013)

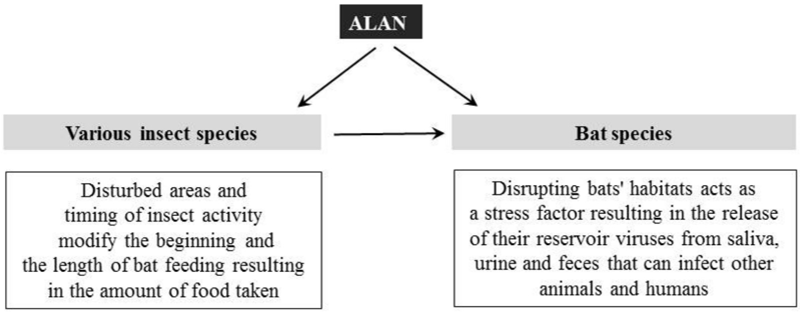
Populations of bats are exposed to several environmental factors, like natural climatic fluctuations (e.g. temperature and humidity variability leading to the seasonal limitations of food availability and subsequent energetic stress), recently accompanied by anthropogenic changes resulting in climate warming or particularly intense storms or floods. Apart from these, such effects of human activity as deforestation or progressive urbanisation (Polak et al. 2011) accompanied by the increasingly frequent contact of bats with humans, and the presence of light and noise pollution (Khan et al. 2020, He et al. 2021) are very strong stressors for bats. These increasingly frequent impacts of anthropogenic stresses alter the balance in bat-virus relationships (Ill. 3.1), cause the breakdown of bats' immunity, facilitate viral shedding, and ultimately result in the spillover viral infections transmitted to other species of animals as well as to humans (Subhudi et al. 2019). As an example, shedding of Hendra viruses by Pteropodide bats resulting in the spillover of infection to horses can be cited (Plowright et al. 2015, Banerjee et al. 2018).

Effect of ALAN on bat physiology and behaviour

The everyday pattern of bat activity is related to the natural light-dark cycle, and sunset affects the time when bats leave their roosts on the way to forage. The significant effects of ALAN on bat physiology and behaviour can be classified as follows (Jung & Threlfall 2016):

1. Twilight is the time when bats start preying. Artificial light delays this time, thus reducing the time of feeding (Boldogh et al. 2007).
2. ALAN fragments the network of the arterial thoroughfares between bat shelters and the feeding grounds. It enforces special bat behaviour, involving light avoidance and the necessity of using alternative (extended) flying paths that require increased energy expenditure (Stone et al. 2009, Stone et al. 2012; Jones et al. 1995, Hölker 2010).
3. Forced extended flying paths create an elevated risk of contact with predators and falling prey to them (Stone et al. 2012).
4. Avoiding migration in lit areas, the light-sensitive bat species lose their foraging fields (Polak et al. 2011).
5. When alternative routes are not available, bat colonies are isolated from their feeding fields, which makes them seek new hiding places (Jones et al. 1995).
6. The insectivorous species of less light-sensitive bats tend to feed near streetlights where more insects attracted by light, such as moths, are present (Langevelde et al. 2011). Such behaviour also limits their safety due to more frequent collisions with vehicles. In the case of young bats, whose flight is slower and less agile, there is increased risk of falling prey to predators (Racey & Swift 1985). In the case of bats feeding in lit areas, changes have been noted in the species and amounts of insects (Ill. 3.2) they consumed (Davies et al. 2012).

7. The presence of ALAN in the hideout and around it results in the decline of fitness in bats. This disturbs the peaceful development of juveniles and promotes immune deficits.
8. The shedding of the zoonotic viruses and increased risk of infectious disease spillover.



Ill. 3.2. ALAN disturbs relationships between insectivorous bats and insects as their prey. Source: own elaboration

Analyses performed in many countries would enable us to determine the most probable sequences of COVID-19 infection development, which have contributed to the spillover of pandemics. The first transmission of virus to man was noted at a Huanan market where, until the end of 2019, live animals (several mammal species, including wild and bred raccoon dogs, foxes, mustelids) were sold. Today, these species are known to be prone to SARS-CoV-2 infection and capable of virus transmission. Huanan city is located in the western part of Hubei province where there are hundreds of caves inhabited by Rinolophidae bats, the hosts of SARS-CoV-2 viruses. Since the outbreak of SARS-CoV-2 pandemics began in this region and high levels of light pollution were noted, the adverse effect of ALAN on the circadian system function in bats was, among other factors, considered responsible for the pandemic spread (Khan et al. 2020, He et al. 2021).

Summary and conclusions

Light pollution is an anthropogenic factor only recently recognised as harmful to humans and the environment. It strongly influences the integrity of the environment and is spreading worldwide very intensively at a rate of about 6% per year. The insidiousness of light pollution lies in the fact that light is generally treated as a factor beneficial to life while ALAN belongs to the strongest disruptors of the biological clock of every organism. Above all, ALAN desynchronises physiology and behaviour of nocturnal animals, represented in this article by bats, which are particularly sensitive to any change in the lighting conditions.

Being a unique group of mammals capable of powered flight, bats have developed a very special activity of the immune system. It allows them to be reservoir hosts of RNA viruses, highly pathogenic for humans and other mammalian species, while bats show no symptoms of the disease. It has been demonstrated that shedding of pathogenic viruses by bats occurs when the infected hosts are submitted to stressful situations, negatively influencing the effectiveness of bats' innate immunity which enables the enhanced replication of viruses.

Temporary food shortage resulting from climatic anomalies, seasonal changes in physiology and energetic stress causing the breakdown or weakening of bats' immunity are factors leading to viral spillover. Other adverse circumstances include the fragmentation of bats' roosting areas, contact with people and, as has been noted during recent spillover of COVID-19 pandemic in some regions of China, the influence of intense light pollution. Increasingly, the presence of ALAN pollution disturbs the delicate balance between the bats' immune system and the viruses hosted in them, leading to the spillover of very dangerous pandemics all over the world. Therefore, particular attention should be paid to the protection of bats' natural living and foraging areas since bats are particularly sensitive to the disturbed darkness of the night caused by the presence of ALAN.

4. Artificial skyglow changes in terms of VIIRS measurements and numerical modelling

Aleš Nečas*
Ladislav Kómar**

Artificial skyglow is a growing problem, the long-term consequences of which we can only speculate on. The effects on animals (Degan et al. 2016, Thums et al. 2016) and humans (Lamphar et al. 2022), which have not yet been thoroughly researched, are widespread and not confined to the vicinity of light sources. Many animal species cannot adapt to this situation as their natural environment is irreversibly disrupted without direct human influence and their behaviour will never be the same (Batra et al. 2020, Gaston et al. 2015).

Humankind is becoming increasingly conscious of the situation and is attempting to mitigate the negative impacts of nighttime lighting (Kyba et al. 2012; Aubé et al. 2016). Many European governments have established legislation, principles, technical standards, and guidelines to limit light pollution. Croatia, France, Germany, Greece, Italy, Malta, Spain, Sweden, and the United Kingdom have all passed legislation related to light pollution. Belgium is one of the most light-polluted countries in Europe. All HPSs will be replaced with LED light sources with sophisticated management in Belgium by 2030. Highway lighting already uses dynamic illumination based on traffic intensity (EU2022.cz 2022).

Dark sky parks were established with as little impact of outside illumination as possible. We can find dark sky parks or their variants, where nature is protected from light pollution all over Europe (in twenty-six countries). However, it is a weak patch on a problem that has been ignored for decades. Six European countries do not yet have dark sky parks, namely Bulgaria, Finland, Italy, Lithuania, Norway and Sweden.

In Slovakia, we have the Act on the Protection, Support, and Development of Public Health and the implementing decree of the Ministry of Health of the Slovak Republic on limiting values of optical radiation and environmental requirements. Terms such as optical radiation, disturbing light, and intense pulsed light are defined in the decree. However, no specific legislation exists to limit light pollution or reduce unwanted, excessive or disturbing light.

To introduce any legislation, technical standard, or non-binding manual for reducing light pollution, quantitative and qualitative assessments of the current level

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of light pollution, both spatially and temporally, are necessary. Numerical models, as one of possible approaches, can not only physically describe the existing state but also predict its changes due to changes in lighting technologies or the local atmosphere. However, numerical models would be worthless without long-term experimental measurements by professionals and enthusiasts.

Several tools for light pollution modelling can more or less accurately simulate the quantities associated with light pollution, such as zenith brightness, horizontal irradiance or radiance distribution over the whole sky vault. However, we need to know the city emission as an input parameter, but city authorities rarely publish this information (i.e. the number and type of street luminaires, the number of illuminated advertising areas, the performance of lamps installed in public, etc.). However, satellite measurements can offer data on city emission and its temporal changes publicly. This work will focus on corrections of satellite data and their subsequent use in modelling light pollution changes. Section 2 presents the basic methods of correcting satellite data and calculating the city lumen output for use in the Skyglow Simulator program. Section 3 depicts changes in the light emission of Trnava (Slovakia) during 2013–2022 and an impact study for constructing a new city district.

Theoretical background

Since 2012, scientists have used satellite data from the Suomi National Polar-Orbiting Partner (Suomi NPP) satellite to determine light pollution worldwide (Goldberg et al. 2013). The device maps the Earth in twenty-two imaging and radiometric bands, which work in the range of wavelengths of electromagnetic radiation from 0.41 to 12.5 μm. It is mainly used to monitor and record data on aerosols, cloud properties, snow, albedo, fire, vegetation, sea level and ocean colour and maps nighttime light emissions in the range of 0.5 to 0.9 μm. (Hillger et al. 2013).

Satellite data corrections

The day-night band (DNB) resolution is 750m/pixel. The NOAA CLASS database also offers raw and corrected satellite data. However, some corrections must be provided manually if we want to compare radiance of the same city pixel at a different time because the changing atmospheric conditions and satellite viewing angle cause variations of the pixel radiance.

The most significant influence on the amount of city lights captured by satellites during cloudless nights is the scattering of aerosol particles. The wavelength dependence of the aerosol optical depth is given by the formula:

$$\tau_a = \tau_{300} \exp\left[1.3 \ln\left(\frac{500}{\lambda}\right)\right] \tag{1}$$

where τ_{500} is the aerosol optical depth measured on 500 nm. The dependence of the molecular absorption on the wavelength can be written as:

$$\tau_m(\lambda) = \frac{0.00879}{\exp(4.09 \ln \lambda)} \tag{2}$$

The atmospheric absorption dependent on the wavelength is then calculated:

$$a_m(\lambda) = \exp\left\{-\left[\tau_a(\lambda) + \tau_m(\lambda)\right]\right\} \tag{3}$$

The total atmospheric absorption thought the spectral sensitivity of the VIIRS is calculated by integration of $a_m(\lambda)$ over the spectral range 500-900 nm.

The measured radiance R_{VIIRS} is then multiplied by the integrated attenuation correction factor a_m and divided by the cosine of the satellite zenith angle Z_S as follows:

$$R = \frac{\left(R_{\mathrm{VIIRS}} a_m\right)}{\cos Z_S} \tag{4}$$

The viewing angle of the satellite determines how much direct radiation from light sources (not-shielded or wrong oriented public lighting, building windows, monument's illumination, vertical advertisements, etc.) and reflected radiation is detected by the satellite. Several statistical models to quantify the relationship between radiance and viewing angle are used (see e.g. Li et al. 2019). Usually, to describe the relationship between the radiance and satellite zenith angle, a quadratic model is applied:

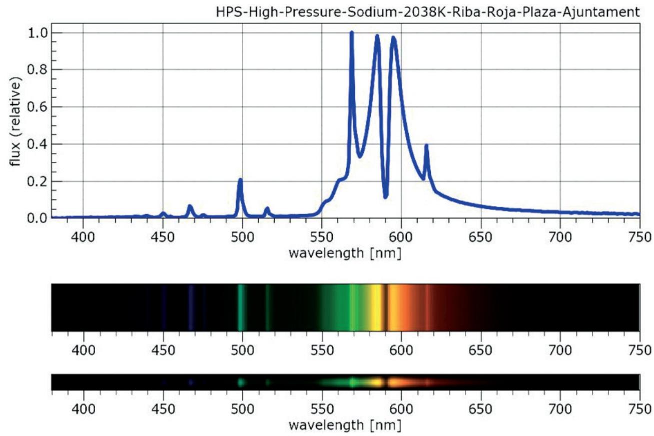
$$c = 1.68 - 1.75 \cos(\theta) + 0.91 \cos^2(\theta) \tag{5}$$

where the correction factor, c, is specified as a function of the satellite viewing zenith angle θ, obtained using VIIRS DNB data from 2015 covering 200 selected cities (Zhang et al. 2019). Radiance values are divided by c to obtain more realistic and comparable radiance values.

Calculation of city lumen output

Each city can be characterised by its lumen output in lumens or electric power used for public lighting in watts. Usually, it is not easy to measure this quantity by ground observations. The city authorities rarely offer information about the city public lighting or other light sources (Wallner et al. 2020). Thus, we are again dependent on satellite measurements. Suppose we can select the light-emitting pixels from the Visible Infrared Imaging Radiometer Suite (VIIRS) data (by selecting only the pixels brighter than some reasonable value, e.g. $1\times10^{-8}\mathrm{W\cdot cm^{-2}\cdot sr^{-1}}$), we can convert this value directly to watts by multiplying it by the city area (in cm^2) and by 2π (solid angle of the hemisphere in steradians). A more complicated but accurate conversion of the quantity of $\mathrm{W\cdot cm^{-2}\cdot sr^{-1}}$ to lumens can be described by the following method:

1. Radiance decomposition to each wavelength according to the spectral distribution of the dominant luminaires (HPS spectrum distribution is depicted on Ill. 4.1). The principle of this method is that each wavelength has its percentage of the total radiance, and then the total radiance can be separated into each wavelength.



Ill. 4.1. Spectrum distribution of the commonly used HPS luminaire (Zamorano et al. 2019)

Conversion from radiance to luminance by integration over the spectrum covered by VIIRS (Cao & Bai 2014):

$$I_V = 638\int_{500}^{900} V(\lambda) R_e I_e(\lambda) d\lambda \qquad (6)$$

where $I_e(\lambda)$ is the decomposed radiance on each wavelength multiplied by the VIIRS DNB relative spectral response function R_e, $V(\lambda)$ is the photopic sensitivity function of the human eye, and the coefficient 683 is the luminous efficacy.

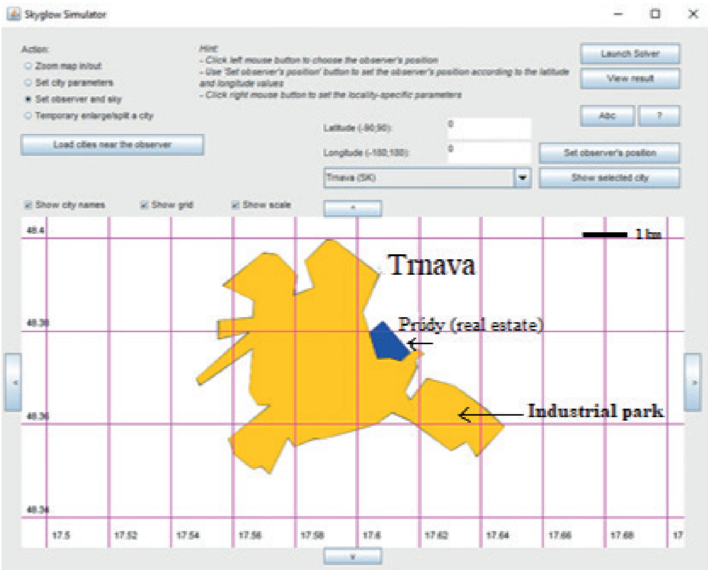
2. The calculated luminance value is multiplied by the city area (in cm^2) and the solid angle of hemisphere 2π.

Conversion of the city radiance to lumen output is performed with the corrected radiance (see section "Satellite data correction") before the integration over the spectral sensitivity of the VIIRS detector. Then, the lumen outputs of two cities or the same city at different times can be compared.

Numerical results

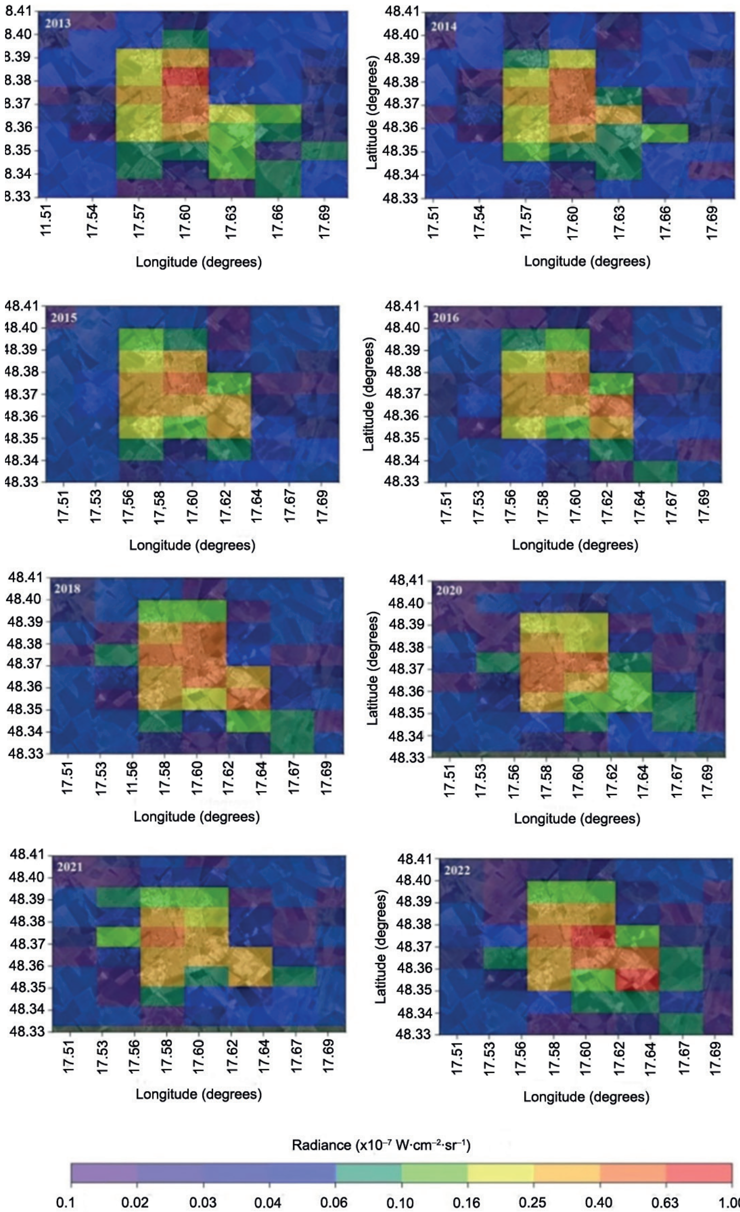
The city of Trnava was selected for its rapidly developing and multifunctional character. It is a regional industrial centre located in western Slovakia with a population of 63 000 inhabitants. The prevailing street lighting is high-pressure sodium (HPS), but public lighting has gradually been replaced with energy-saving luminaires since 2013, which corresponds to lower emissions from the city centre as is visible in Ill. 4.3. The lighting of the historical buildings in the city centre was replaced between 2018 and 2020. There is an industrial park with a car factory in the suburb of Trnava, with an area of 217 700 m^2 that employs approximately 5000 people. Light emissions from this part of the city were continuously increasing until 2020. The subsequent decrease is probably due to the Covid crisis and the lockdown of factories. Ill. 4.2 shows Trnava visualised in the Skyglow Simulator software as a yellow polygon with a new real estate Prúdy as a blue polygon. The diameter of the city is approximately 5 km.

VIIRS DNB data for cloudless nights around the new moon were selected and acquired from NOAA Comprehensive Large Array-Data Stewardship System (CLASS) website (www.avl.class.noaa.gov). Cloudiness over the selected region was analysed by Clear Sky Confidence as a VIIRS data product.



Ill. 4.2. City of Trnava (yellow) with Prúdy real estate (blue) simulated in Skyglow Simulator software. Source: own elaboration

If the threshold is higher than 0.98, the sky can be considered as clear. Dates in March-April were selected due to the absence of snow cover and similarity in vegetation growth. City emissions are compared in Ill. 4.3 for the decade from 2013 to 2022.



Ill. 4.3. Comparison of Trnava light emission from corrected VIIRS data for the period 2013-2022. Source: own elaboration

VIIRS DNB data is noisy, even when it is aggregated over time. The same holds true for instantaneous data sets presented in this study. Therefore, the noise background should be identified first and subtracted from the measured radiance. According to the work of Yuan et al. (Yuan et al. 2019), distinct areas without artificial lighting have radiance thresholds in the range 0.2–0.4×10^{-9} W·cm^{-2}·sr^{-1} (average 0.29×10^{-9} W·cm^{-2}·sr^{-1} with a standard deviation 0.12). Therefore, all the pixels with lower radiance than the average can be classified as the noise background and subtracted from measured data as bias. According to Liao et al., the radiometric calibration uncertainty is approximately 8.9% across the entire radiometric range (Liao et al. 2013).

Table 4.1. Measured total corrected radiance of Trnava, aerosol optical depth, satellite zenith angle, estimated artificially lit area and calculated total lumen output

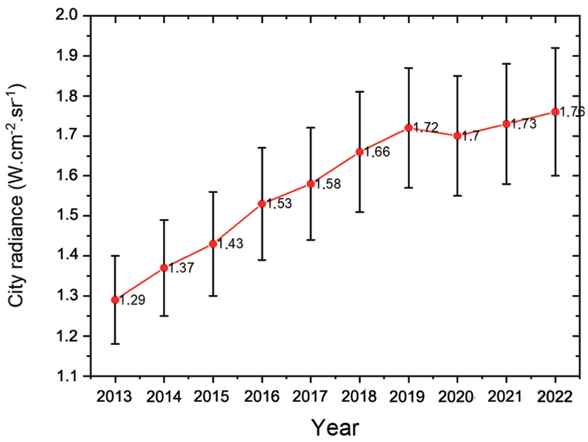
Date	Aerosol optical depth (-)	Satellite zenith angle (deg)	Total radiance (10^{-9} W·cm^{-2}·sr^{-1})	Artificially lit area (km^2)	Lumen output (10^8 lm)
3/17/2013	0.24	7.9	1.29 ± 0.11	45	2.53 ± 0.23
3/30/2014	0.19	23.5	1.37 ± 0.12	45	2.69 ± 0.24
3/20/2015	0.23	44.6	1.43 ± 0.13	46	2.80 ± 0.25
4/12/2016	0.34	39.4	1.53 ± 0.14	46	2.84 ± 0.25
3/28/2017	0.16	27.5	1.58 ± 0.14	46	2.93 ± 0.26
4/19/2018	0.22	54.2	1.66 ± 0.15	47	3.08 ± 0.27
3/31/2019	0.17	44.9	1.72 ± 0.15	49	3.11 ± 0.28
3/18/2020	0.16	9.3	1.70 ± 0.15	49	3.10 ± 0.28
3/08/2021	0.24	17.8	1.73 ± 0.15	50	3.15 ± 0.28
3/01/2022	0.14	32.8	1.76 ± 0.16	51	3.29 ± 0.29

Table 4.2. Increase of the city emission in different periods

2013-2016	2016-2019	2019-2022	2013-2022
+12.25%	+9.51%	+5.79%	+30.0%

Table 4.1 presents the total corrected city radiance and its uncertainty, satellite zenith angle, AOD acquired from MODIS satellite data, estimated artificially lit area, and calculated total lumen output for selected dates. The artificially lit area is calculated as the number of radiating pixels brighter than the limit radiance multiplied by the area of one DNB pixel (0.75×0.75 km). Of course, this is only the estimated area due to the slightly changing pixel area with the satellite viewing angle and limited spatial resolution of the DNB. The limit pixel radiance 1×10^{-8} W·cm^{-2}·sr^{-1} is determined from the DNB radiance on actual Google Earth map layer defining the pixels belonging to the built-up area of the city. Again, it is just an approximated value because of the possible fluctuation of the intensity of street lighting in the past due to the luminaire renewal. As shown, the artificially lit area (pixels brighter than 1×10^{-8} W·cm^{-2}·sr^{-1}) is increasing due to the growing urbanisation in the city suburbs. Corresponding total radiance and lumen output are consequently increasing.

Table 4.2 shows the percentage increase with a three-year time step. However, comparing the radiance and lumen output each year is not very efficient because of the measurement uncertainty which exceeds the yearly change of the measured value. Therefore, it is reasonable to compare data in a three-year time step as is presented in Table 4.2.



Ill. 4.4. Total corrected city radiance with error margins

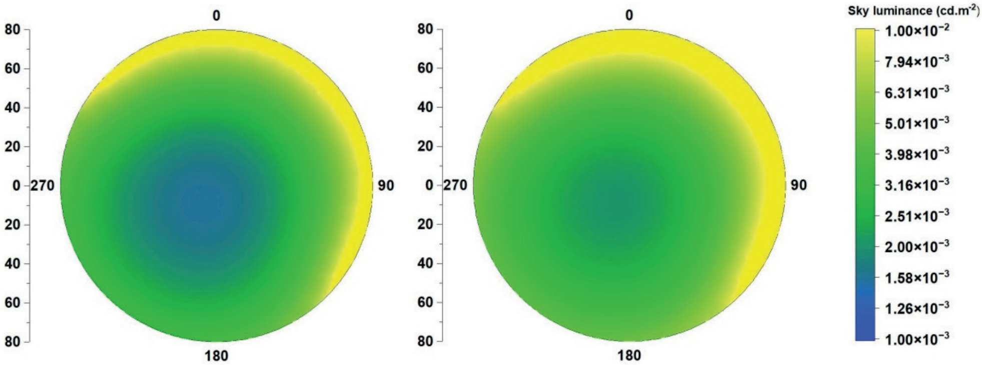
Ill. 4.4 depicts the total corrected city radiance for each year corresponding to Table 1. As is shown, the error margins are usually higher than the radiance difference from year to year, thus a higher time step makes more sense

Zenith sky brightness and corresponding horizontal illuminance is compared as a next step. Skyglow Simulator described in (Kocifaj & Kundracik 2016) was used to determine the zenith brightness and horizontal illuminance for the period 2013-2022. Calculated total emissions (in lumens) from VIIRS data for the city of Trnava was used as input for the calculations. Acquired AOD from Table1, HPS light sources, and Garstang parameters: F = 0.1 and G = 0.1, were considered in the numerical modelling. Continuous increases of both factors are evident in correlations with the total lumen output of the city.

Table 4.3. Zenith brightness, horizontal illuminance, and its relative deviation during the examined years in the centre of Trnava

Year	Zenith brightness (mag·arcsec^{-2})	Diffuse horizontal Illuminance (lux)	Relative deviation (%)
2013	19.57	1.13×10^{-2}	0
2016	19.05	1.32×10^{-2}	+16.81
2019	18.95	1.45×10^{-2}	+9.85
2022	18.92	1.53×10^{-2}	+5.52

Ill. 4.5 shows the night sky luminance distribution in 2013 (left) and 2022 (right) for the observer in the city centre. It is evident that zenith radiance suffers from the city expansion, and all parts of the sky are exposed to increasing night lighting. The change in zenith brightness over the considered ten years is 0.65 mag·arcsec^{-2}, as seen in Table 4.3. The relative deviation of horizontal illuminance has decreased slightly in the last three years. However, slowing down the city expansion is only a temporary phenomenon. New housing estate projects are planned, and the construction of some of them has already commenced.



Ill. 4.5. Night sky brightness (in cd·m^{-2}) as seen by an observer in the centre of Trnava in 2013 (left) and 2022 (right). Source: own elaboration

The construction of the new Prúdy housing estate, with an area of 11 ha, started in 2021. Residential (19) and multifunctional (8) buildings are planned with more than 1300 apartments for approximately 4000 inhabitants. The total planned power of the public lighting with 279 LED luminaires is 18.1 kW without any impact study on light pollution. We tried to briefly analyse what light pollution changes will occur when the new housing estate is finished, and the public lighting is turned on. Well-shielded LEDs with Garstang parameters F = 0.02, G = 0.1, and AOD = 0.15 were used in modelling. The numerical results are presented in Table 4 for the observer situated in the centre of the new block of flats.

Table 4.4. Zenith luminance and horizontal illuminance before and after constructing the new block of flats in Trnava. The observer is situated in the centre of the new Prúdy housing estate

	Zenith luminance (mag·arcsec^{-2})	Horizontal illuminance (lux)
Before	20.04	8.29×10^{-3}
After	19.03	1.50×10^{-2}

Conclusions

In the last decade, there has been increased interest in solving the problem of light pollution. This is a consequence of new technological solutions for lighting, such as the transition to more energy-efficient luminaires but also the fact that we can have a better look at this phenomenon from the Earth's orbit. We can monitor the night light changes and our first measures to reduce it. We have learned to quantify, measure and model this phenomenon, but there is still a long way to go to know all the contexts, especially the consequences.

In our work, we have focused on processing satellite measurements and modelling light pollution using this data as the input. We have shown a simple but necessary correction of satellite data for their comparison in the time series. We presented the calculation of the lumen output of the city from the satellite measurements, which is crucial information for numerical modelling that is often unavailable. For the city of Trnava, we analysed emissions over the last decade and found an increase of about 30%.

A constant problem in constructing new urban districts or changing street lighting is the absence of impact studies. The only criterion is reducing electricity consumption and cost savings. However, the impact of new lighting systems on the night sky brightness and the effect of the blue component of the usually installed luminaires on the ecosystem are often ignored. Therefore, we did a short impact study for the new housing estate in Trnava that is currently under construction.

Acknowledgments

This work was supported by the Slovak National Grant Agency VEGA under contract number 2/0095/20 and the Slovak Research and Development Agency, grant number APVV-18-0014.

5. Light pollution in the area of the planned construction of a nuclear power plant in the Pomeranian Voivodeship in Poland

Tomasz Ściężor*
Anna Czaplicka**

On September 5–7, 2017, the XXVII Economic Forum took place in Krynica-Zdrój. It was attended by politicians from Poland and many other countries in the region as well as economists, analysts and presidents of the largest companies from a wide range of industries. The energy trends and regional solutions, challenges for the Polish fuel sector, energy policy dilemmas, the clean energy problem and energy supply diversification were discussed (Klein 2017). The Minister of Energy, Krzysztof Tchórzewski, announced the intention to build the first Polish nuclear power plant in order to meet the obligations related to the limitation of CO_2 emission. Many locations in Poland were taken into account, but eventually Lubiatowo-Kopalino and Choczewo (both in Choczewo commune) and Żarnowiec (in Gniewino and Krokowa communes) were chosen in the Pomeranian Voivodeship. In 2016, the Choczewo location was rejected for ecological reasons, so two locations remained for the choice to be made from: Lubiatowo-Kopalino and Żarnowiec. It was announced that the first block could start operating in 2030, and the next blocks at intervals of several years.

The members of the Light Pollution Monitoring Laboratory (LPML), operating at Cracow University of Technology since 2015, found that it was necessary to measure the level of light pollution in the form of artificial sky glow in the indicated locations. It was found that this is the last moment to perform this type of analysis in an undisturbed Polish coastal zone natural area. The described research will also make it possible to make future determinations of the impact of the nuclear power plant on the night environment both during its construction and after its completion.

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History of the issue

Discussions have been ongoing for years as to whether nuclear power plants should operate in Poland. The demand for electricity is constantly growing. Problems with environmental pollution by coal-fired power plants and the ongoing energy crisis force decision-makers to look for alternative energy sources.

The construction of a nuclear power plant in Poland has long been considered. The establishment of the Institute for Nuclear Research (IBJ) in Świerk near Otwock in 1955 and the launch of the first experimental nuclear reactor in Poland, EWA, at IBJ on 14 June 1958, (operated until 24 February 1995) was the beginning of activities in this area (https://www.ncbj.gov.pl/en/o-nas/history-ncbj). On 12 August 1971, the Presidium of the Government decided to build a nuclear power plant and perform the preparatory work (Jezierski 2006). The Planning Commission at the Council of Ministers decided on 19 December 1972 that the power plant would be located in Żarnowiec in Pomerania. On 28 February 1974, an agreement was signed between the Government of the People's Republic of Poland and the Government of the USSR with regard to cooperation in the construction of a nuclear power plant. On 18 January 1982, the Council of Ministers adopted a resolution on the construction of the Żarnowiec Nuclear Power Plant, comprising two power units of the Soviet WWER-440 type. The first power unit with a capacity of 465 MW was to be launched in 1989, and the second in 1990. Construction began on 31 March 1982, but works were stopped in the early nineteen-nineties, mainly under the pressure of protests by opponents of nuclear power. Only the accompanying investment – the pumped-storage power plant – has been completed. In the nineteen-eighties, the construction of the Warta Nuclear Power Plant in Klempicz was also planned (Energetyka Jądrowa 2013).

On 4 January 2005, the government of Marek Belka adopted the document Energy Policy of Poland until 2025 (M.P. 2005), in which it was written: "Due to the need to diversify primary energy carriers and the need to reduce greenhouse gas emissions into the atmosphere, it becomes justified to introduce nuclear power system. Since the forecasts indicate the need to obtain electricity from a nuclear power plant in the second decade of the considered period, taking into account the length of the investment cycle, it is necessary to immediately start a public debate on this subject. On 9 November 2008 in Gdańsk, Prime Minister Donald Tusk announced the construction of at least two nuclear power plants in northern Poland (Jamroż 2008). Probable locations again include Żarnowiec in Pomerania and also a few other areas in the Podlasie region. In January 2009, the Polish government decided to start work on the Polish Nuclear Energy Program (NIK 2018). The task related to the construction and operation of the first Polish nuclear power plant which was entrusted to PGE Polska Grupa Energetyczna SA (PGE 2010). In 2010, the special-purpose entity PGE EJ 1 was established, the task of which was to build a nuclear power plant in Poland with a capacity of approximately 3 GW. The first task was to identify the possible locations of the object. On 8 January 2010, the Ministry of Economy published a list of twenty-eight localities that are considered for the location of the first nuclear power plant in Poland (FORSAL 2010). On 25 November 2010, PGE EJ 1 indicated the three most favourable places: Żarnowiec, Choczewo and Gąski, located in the coastal belt of the Pomeranian province (https://biznes.interia.pl/gospodarka/news-pge-podala-trzy-potencjalne-lokalizacje-elektrowni-jadrowej,nId,3778120) (Ill. 5.1).

Ill. 5.1. Locations of the nuclear power plant proposed by PGE. Source: https://nuclear.pl/wiadomosci,news,16021501,0,0.html

In February 2012, more than 94% of the residents of the Mielno commune who participated in the referendum were against the location of the nuclear power plant in the summer resort village of Gąski, which resulted in the rejection of this location (Forbes 2012). Finally, PGE EJ 1 also abandoned the construction of the power plant in the Choczewo location in the Choczewo commune (https://nuclear.pl/wiadomosci,news,16021501,0,0.html). The investor admitted that the construction of a nuclear power plant in the area of the Wydma Lubiatowska may significantly affect the protection of the Białogóra Natura 2000 Area adjacent to this location. Within the same commune, however, the Lubiatowo-Kopalino site was still considered (Derewienko 2016).

In 2016 PGE EJ 1 ultimately indicated two regions in which to perform both location and environmental research, all in the province of the Pomeranian Voivodeship: Żarnowiec (Krokowa commune), on the site of the once started construction of a nuclear power plant, and Lubiatowo-Kopalino (Choczewo commune) (Urbaniak 2019).

The commencement and then launch of the investment in one of these locations will surely cause the degradation of the natural environment, particularly including an increase of light pollution in the form of artificial sky glow. The scientists of the

LPML decided to conduct an analysis of the current state of light pollution at both of the above-mentioned regions, as an introduction to the subsequent monitoring of these regions during and after the implementation of the investment.

After conducting the research and preparing the text of this publication, in October 2022 the Polish government announced that the nuclear power plant will be built in the Lubiatowo-Kopalino region in the Choczewo commune in Pomerania (Boroń 2022).

The natural environment in the immediate vicinity of the planned location of the nuclear power plant

The first of the considered locations for a nuclear power plant is Żarnowieckie Lake on the border of two communes, Gniewino and Krokowa (border of Wejherowo and Puck poviats, Pomeranian Voivodship) in the Żarnowiec Upland. It is a ribbon lake, the bottom of which is located below sea level (crypto depression). The glacial channel is located between two moraine hills – Kępa Żarnowiecka (from the east) and Kępa Gniewińska (from the west). Throughout the length of the lake, from south to north, the Piaśnica River runs and then flows into the Baltic Sea about 4 km to the north. Additionally, the Struga Bychowska stream flows into the lake from the west. The area of Żarnowieckie Lake is 1431 ha, with a length of 7.6 km, a width of 2.6 km, a maximum depth of 19.4 m (Choiński 2006) and a capacity of 120.8415 million m^3 (Karkowski & Nabagło 2020). The surface level of the lake varies by about 1 m in a daily cycle, which is related to the operation of the pumped-storage power plant. The flora of the lake includes hornwort, Canadian waterweed, water duckweed, lake poblin, small duckweed, water arrowroot and water cattail. Among the fish, pike, tench, bream, perch, roach, crucian carpand chub dominate. Also in the waters of this lake are found catfish, eels, asp, carp, grayling, trout, zander, barbel, nase, vimba, grass carp, sea trout, salmon and sows (Radtke et al. 2010). In addition, the northern edges of the lake are inhabited by fish species protected by law: red feathers, ides, alas, black and sand gobies, tusks, western sturgeons, gudgeons, goats, chicks and slimes (Skowroński 2011). The lake is dominated by beech and beech-oak forests. The south-western shore of Żarnowieckie Lake has been classified as a Natura 2000 Area Opalińskie Buczyny (Karkowski & Nabagło 2020). The refuge includes unique and well-preserved spring communities, not only in the scale of the country but also of all of the European lowland. Noteworthy is a large area of beech forests, including the fertile Pomeranian beech forest (Natura 2000). Moreover, the gutter lake Żarnowieckie is an ecological corridor of supra-regional importance.

The second of the researched locations is the area located on the Baltic Sea coast in the vicinity of the villages of Lubiatowo and Kopalino. Both villages, located in the Choczewo commune (poviat of Wejherowo, Pomeranian Voivodeship), lie within the area of the Nadmorski Park Krajobrazowy (Seaside Landscape Park). Within a distance of approx. 20 km from the planned location of the nuclear power plant, there is the Słowiński National Park and several nature reserves (e.g. in the vicinity of Babnica, Choczowskie Cisy, Widowo, Mierzeja Sarbska), i.e. the strictest legal forms of nature protection, where nature protection has priority over other aspects of activity. The Mierzeja Sarbska nature reserve stretches just 4 km to the west of the investment. It is one of the most beautiful fragments of the Polish coast, it is a kind of miniature of Słowiński National Park, located a further few kilometres to the west (Kąckowska 2016). From the north, the reserve adjoins the beach, and from the south the reserve meets Sarbsko Lake. The Mierzeja Sarbska reserve protects a narrow strip (up to 1 km wide) of coastal dunes. The greater part of the reserve, almost 400 ha, is covered by forest communities, mainly belonging to various forms of the crowberry forest association (*Empetro nigri-Pinetum*). In the depressions between the dunes, wet willow-briar heaths, rare in Poland, are formed. The value of this area is increased by thickets with European waxwort (*Myrica gala*), a legally protected Atlantic species, which is very rare and endangered in Poland. The flora of the reserve shows outstanding natural values due to the exceptionally high concentration of rare and endangered species in Pomerania and even all of Poland. Currently, there are about 340 species of vascular plants in the Mierzeja Sarbska reserve, including twenty-eight legally protected species. Particularly noteworthy are: peat violet, brown bracken, turf cottongrass, round-leaved, long-leaved and intermediate sundew, swamp sedge, European waxwort and linseed – a species of European importance.

In addition, there are several Natura 2000 areas related to the protection of habitats and birds (such as Lubiatowskie Bory Bażynowe, Mierzeja Sarbska, Pobrzeże Słowińskie, Ostoje Słowińskie, Widmowo) within the countries of the European Union (Karkowski & Nabagło 2020). Parallel to the shore, there is the Natura 2000 Area Przybrzeżne wody Bałtyku (Coastal Waters of the Baltic Sea). The seabed is uneven along this line, its denivelations reach 3 m. This area is a bird sanctuary of European importance. It is worth noting that two species of birds, the black-throated diver and the red-throated diver (from Annex I of the Birds Directive) winter in this area. Populations of long-tailed duck, guillemot and uhla are also of particular importance (Karkowski and Nabagło 2020). Occasionally, there are also marine mammals, which include grey and ringed seals and porpoises, which are under special protection as organisms threatened with extinction. In both areas, there are forest animals such as deers, roe deers, fallow deers, wild boars, foxes, martens, badgers, hares, and among birds there are lesser spotted eagles, eagle owls, kingfishers, and white-tailed eagles.

The location of the nuclear power plant was chosen on the shores of the Baltic Sea because of the possibility of cooling the nuclear reactors and discharging the water heated by them into surface waters. In Żarnowieckie Lake, this action would increase its temperature by 1 to 2°C, which would have a significant impact on the ecosystem of the entire lake. Nevertheless, it seems that water from the Baltic Sea drawn through pipelines could be used to cool the nuclear reactors of the power plant located in Żarnowiec, and the heated water could also be discharged into the Baltic Sea. Perhaps this would increase the cost of the investment, but it would probably be more beneficial for the natural environment.

Time and space conditions of measurements

Measurement time range

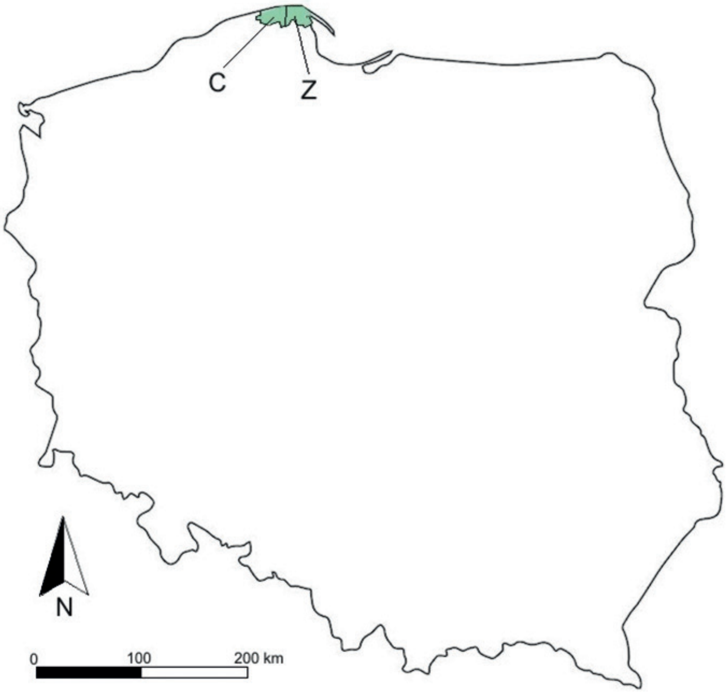
Measurements were made on two consecutive nights: 15/16 October and 16/17 October 2020. These nights were chosen due to the need to be free from the potential influence of moonlight on the measurement results. The new moon fell on the evening of 16 October at 21:31 CEST, which ensured a completely moonless sky on both measurement nights.

The second of the necessary conditions was to ensure that the twilight effects did not affect the brightness of the night sky. This condition is met during the astronomical night, i.e. when the sun on the celestial sphere sinks below the horizon to a depth of more than 18°. In the research area, this condition was met on the given dates between 19:47 CEST and 05:22 CEST.

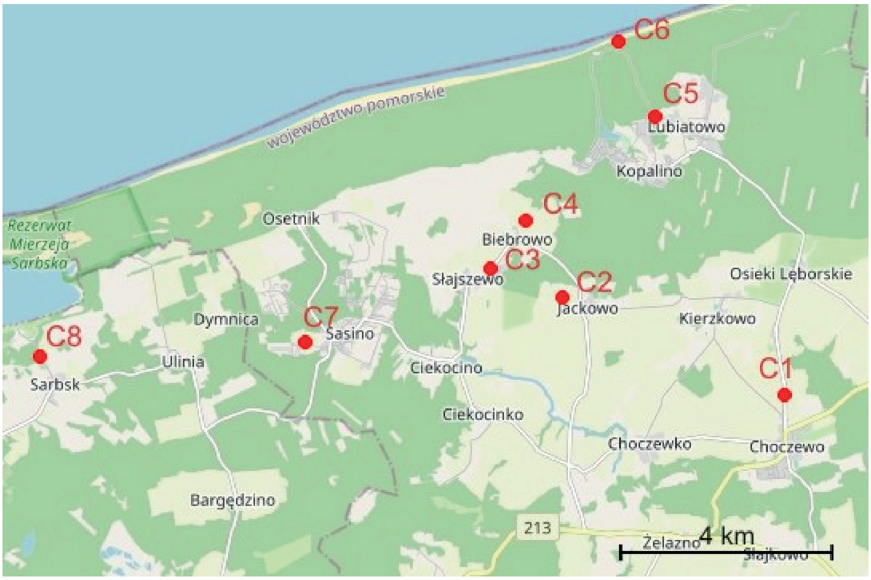
In the case of the first measurement night (15/16 October), the measurements started at 22:29 CEST, ended at 04:02 CEST. In the case of the second measurement night (16/17 October), the measurements started at 20:05 CEST and ended at 01:00 CEST. Therefore, the condition of doing the research during the astronomical night was met in both cases.

Spatial range of measurements

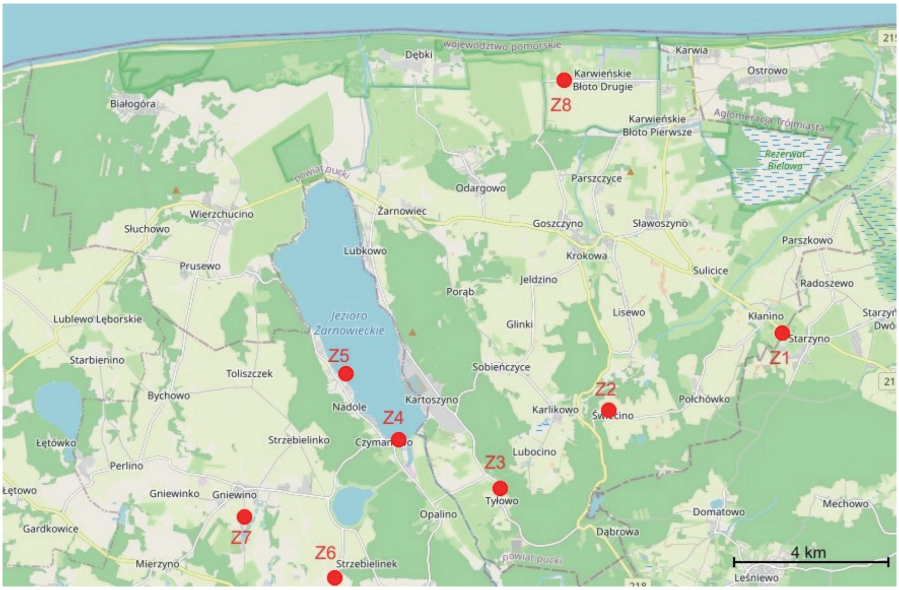
During both the first and second night, measurements were made at sixteen points located in the described regions in the communes of Choczewo (region C) and Żarnowiec (region Z) (Ill. 5.2; Table 5.1). Region C, with an area of approx. 72 km^2, included eight measurement points: C1-C8 (Ill. 5.3). Region Z, with an area of approx. 142 km^2, included another eight measurement points: Z1-Z8 (Ill. 5.4). In total, in both regions, 200 km were driven each night, moving between successive research points, which results in a long, several-hour research period in each measurement night. It should be remembered that this may have a potential impact on the measured parameters, as one should take into account the possibility of reducing residential lighting as the night progresses. However, this effect is negligibly small, because the dominant impact on the formation of city sky glow is municipal street lighting (Ściężor 2019).



Ill. 5.2. Map of Poland with marked Pomeranian communes of Choczewo (region C) and Żarnowiec (region Z). Source: own elaboration



Ill. 5.3. Map of the Choczewo region (C) with marked measurement points (© OpenStreetMap authors)



Ill. 5.4. Map of the Żarnowiec region (Z) with marked measurement points (© OpenStreetMap authors)

Table 5.1. Coordinates of the measurement points

Point	Coordinates [°]	
	Latitude (N)	Longitude (E)
C1	54.7501	17.8918
C2	54.7660	17.8284
C3	54.7698	17.7989
C4	54.7793	17.8098
C5	54.7990	17.8530
C6	54.8112	17.8326
C7	54.7585	17.6646
C8	54.7558	17.6646
Z1	54.7548	18.2546
Z2	54.7362	18.1720
Z3	54.7197	18.1171
Z4	54.7291	18.0791
Z5	54.7459	18.0547
Z6	54.6912	18.0499
Z7	54.7109	18.0108
Z8	54.8212	18.1440

Weather conditions

The weather conditions between the measurement nights differed significantly. On the night of 15/16 October at virtually every measurement point, the sky was completely covered with layered clouds of the low and middle levels (*Stratus* and *Nimbostratus* types), with a base height of approx. 250 m to approx. 800 m (this data, read during measurements from current meteorological reports of the Gdańsk-Rębiechowo airport (https://pl.allmetsat.com/metar-taf/polska.php?icao=EPGD), located approx. 40 km from the research areas, was compared with the observed local situation). Only at the end of the measurements made that night (points C7 and C8) did the cloud base rise to over 1000 m (Table 5.2) (Ill. 5.5, Ill. 5.6).

On the night of 16/17October, the sky was also completely covered with mid-level layered clouds (of the *Nimbostratus* type) at some measurement points (Z3, Z4, Z5, C1, C5) with a base height of approx. 400 m to approx. 1200 m. However, in several points, there was a completely cloudless sky (Z1, Z2, C2, C3, C4, C6, C7, C8). At two points (Z6, Z7) the cloudless sky was limited to the zenith where the measurements of the surface brightness of the sky were made – this is marked in the tables (Table 5.3) (Ill. 5.7, Ill. 5.8, Ill. 5.9, Ill. 5.10).

Table 5.2. Weather conditions at the measurement points at night on 15/16 October 2020

Point	Time CEST	Clouds		Air temperature [°C]	Notes
		Base [m]	Cloudiness [%]		
C1	01:34	244/427	95	7.5	Overcast
C2	03:10	549	100	9.5	Overcast
C3	03:28	823	100	10.0	Overcast
C4	03:20	823	100	9.5	Overcast
C5	01:54	91/457/610	100	9.5	Overcast
C6	02:30	549	60	9.5	Overcast with patches
C7	03:45	1346	100	10.0	Overcast
C8	04:02	1346	100	9.0	Overcast
Z1	22:49	265	100	10.0	Overcast
Z2	22:29	265	100	9.0	Overcast
Z3	23:45	274/427	100	8.5	Overcast
Z4	00:10	91/366/671	90	9.5	Overcast
Z5	00:25	91/366/671	80	10.5	Broken clouds, visible stars in the gaps
Z6	00:45	366/488	80	8.5	Overcast
Z7	01:06	366/488	90	8.0	Overcast
Z8	23:12	274/427	100	10.5	Overcast

Tab. 5.3. Weather conditions at the measurement points at night on 16/17 October 2020

Point	Time CEST	Clouds		Air temperature [°C]	Notes
		Base [m]	Cloudiness [%]		
C1	22:30 23:35	1006/1311 518/610/975	100 100	6.0 6.5	Heavy rain, measurements from the car, repeated after an hour with less rain
C2	00:05	–	0	6.0	Cloudless sky; Bortle: 3
C3	00:21	–	0	5.0	Cloudless sky; Bortle: 3; passing waves of fog
C4	00:13	–	0	5.5	Cloudless sky; Bortle: 3
C5	22:45	640/1036/1219	95	6.5	Variable cloudiness during the measurement
C6	23:10	–	0	6.5	Cloudless sky; Bortle: 3
C7	00:38	–	0	4.0	Cloudless sky; Bortle: 3
C8	01:00	–	0	4.0	Cloudless sky; Bortle: 3
Z1	20:25	700	0	7.0	Few cumulus clouds visible about 40° from the zenith
Z2	20:05	–	0	6.0	Cloudless sky, visible milky way
Z3	21:10	396/823	100	5.5	Medium clouds, broken; full cloudiness at the zenith, darker patches about 30° from the zenith.
Z4	21:22	518/823	100	6.0	Rain
Z5	21:35	518/823	100	6.5	Overcast
Z6	21:49	762/1280	20	7.0	Zenith gap in the clouds with a diameter of 30°.
Z7	22:05	762/1280	20	7.0	Zenith gap in the clouds with a diameter of 15°.
Z8	20:45	396/823	0	7.0	Cloudless at the zenith, about 30° from the zenith intermittent clouds

Ill. 5.5. Photography of the overcast sky at the Z8 measurement point at night on 15/16 October 2020. Visible are the sky glows of Wejherowo (left) and Krokowa (right) (photo: T. Ściężor)

Ill. 5.6. Photography of the overcast sky at the Z5 measurement point at night on 15/16 October 2020. Visible is the sky glow of Wejherowo over the surface of Żarnowieckie Lake (photo: T. Ściężor)

Ill. 5.7. Photography of a partly cloudy sky at the C7 measurement point on the night of 16/17 October, 2020. On the left there are sky glows of the nearby villages of Jackowo and Kierzkowo, on the right the distant sky glow of Wejherowo (photo: T. Ściężor)

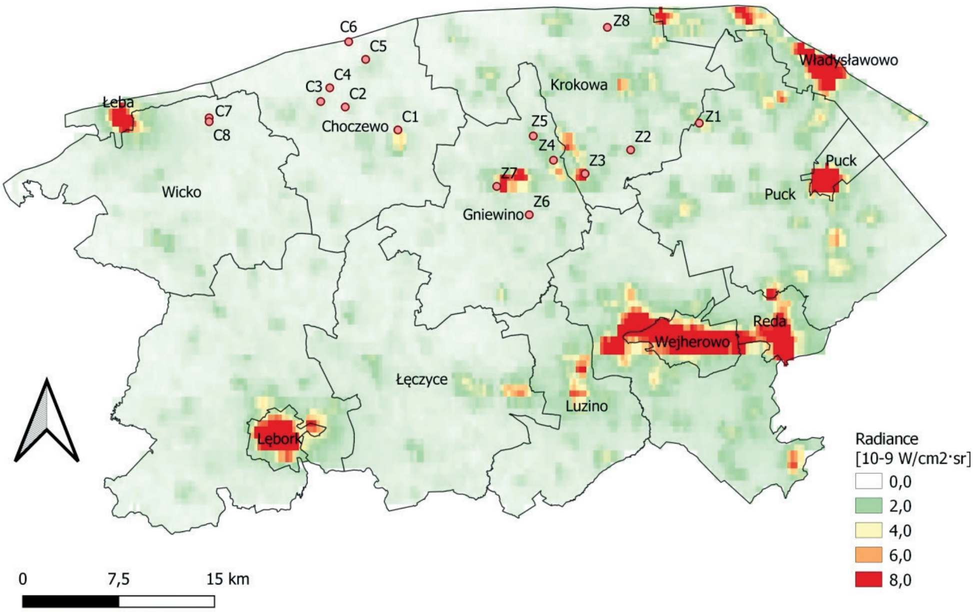
Ill. 5.8. Photography of a partly cloudy sky at the C2 measurement point on the night of 16/17 October 2020. Visible is the sky glow of Lębork (photo: T. Ściężor)

Ill. 5.9. Photography of a cloudless sky at the zenith at the C7 measurement point at night on 16/17 October 2020 (photo: T. Ściężor)

Ill. 5.10. Photography of a cloudless sky at the zenith at the C8 measurement point at night on 16/17 October 2020 (photo: T. Ściężor)

Analysis of the level of light pollution in the regions of research

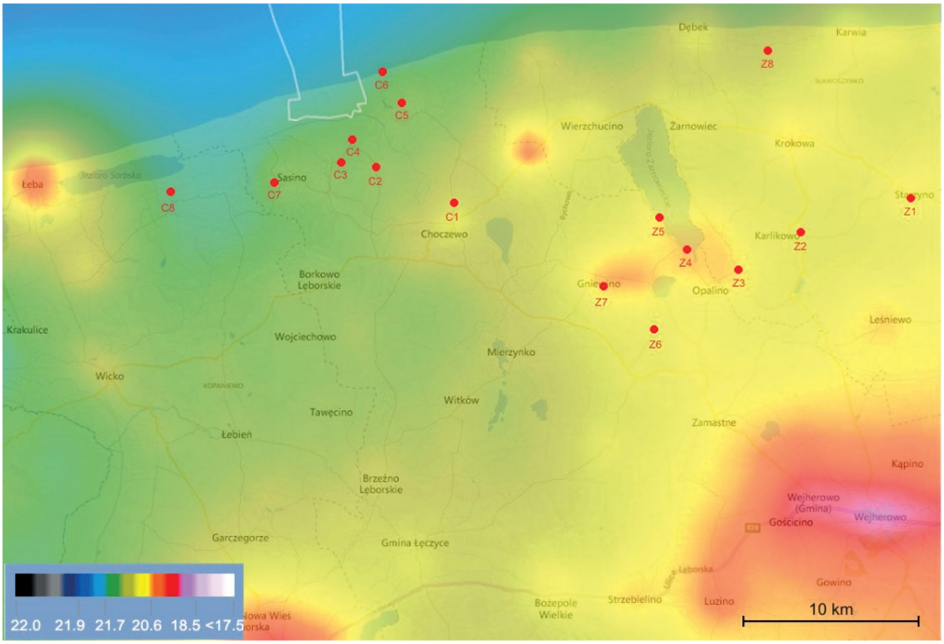
For the initial analysis, both the map of satellite-measured radiance for October 2023 (based on: VIIRS 2023) (Ill. 5.11) and the map of the surface brightness of the night sky resulting from the theoretical model (Falchi et al. 2016) were used (Ill. 5.12).



Ill. 5.11. Radiance measured by satellite in October 2020 for researched regions in a few Pomeranian communes, with marked locations of measurement points. The scale on the right is expressed in units of 10^{-9} W·cm^{-2}·sr^{-1} (based on: VIIRS 2023).

The radiance map shows that the main sources of light pollution in the area of research are the towns of Wejherowo, Reda, Puck, Władysławowo, Łeba and Lębork, for which the radiance is approx. (20–30)·10^{-9} W·cm^{-2}·sr^{-1}. It should also be noted that there is a clear difference in the average radiance from region Z (approx. 0.8×10^{-9} W·cm^{-2}·sr^{-1}) compared to the average radiance from region C (approx. 0.1×10^{-9} W·cm^{-2}·sr^{-1}). This difference should be associated with a much smaller number of villages and nearby cities, and thus a lower population density in region C compared to region Z.

The same effect is also visible on the model map, which predicts a zenith surface brightness of a cloudless night sky of about 21.0 mag·arcsec^{-2} (0.43 mcd·m^{-2}) for the region Z, while for the region C, this value is equal to about 21.5 mag·arcsec^{-2} (0.27 mcd·m^{-2}). The October 2020 radiance values (based on: VIIRS 2023) as well as model values of brightness of the night sky at the zenith (Falchi et al. 2016) read from the above maps for measurement points are presented in Table 5.4. These values were verified as part of the research.



Ill. 5.12. Model map of the brightness of the cloudless night sky in the researched regions in 2015, with marked locations of measurement points. The given scale is expressed in units of mag·arcsec^{-2} (Falchi et al. 2016). The maximum spatial scope of the investment approved in 2022 is marked with a white outline (Polski Atom 2022)

Tab. 5.4. Values of the surface brightness of the night sky (S_a) predicted by the model for the study area (Falchi et al. 2016), corresponding luminance values (L) and the satellite-measured radiance (based on: VIIRS 2023) for the coordinates of the measurement points

Measurement point	Surface brightness of the night sky		Radiance (Oct 2020) (10^{-9} W·cm^{-2}·sr^{-1})
	S_a (mag·arcsec^{-2})	L (mcd·m^{-2})	
C1	21.20	0.36	1.14
C2	21.47	0.28	0.71
C3	21.52	0.27	0.79
C4	21.59	0.25	0.41
C5	21.52	0.27	1.07
C6	21.67	0.23	0.36
C7	21.56	0.26	0.67
C8	21.67	0.23	0.67
Z1	20.86	0.49	2.10
Z2	21.08	0.40	1.52
Z3	20.81	0.52	8.36

Tab. 5.4 (cont.)

Z4	20.59	0.63	2.57
Z5	20.94	0.46	2.38
Z6	21.02	0.43	0.82
Z7	20.83	0.51	0.96
Z8	21.31	0.33	0.67

Principles of measurements

Measuring apparatus

Measurements of the surface brightness of the night sky were made using the Sky Quality Meters (SQM) by Unihedron (Cinzano 2005). SQMs are produced in several versions. In the described research, manually triggered SQM and SQM-L models were used. These meters differ in the angle of light collection, which in the case of SQM reaches up to 60° from the axis of the device (half width is approx. 42°), while for SQM-L, this angle is only 20° (half width is approx. 10°) thanks to a simple optical system. As a result, the SQM provide the average surface brightness over a large area of the celestial sphere, while the SQM-L enables measurement of the surface brightness in a selected direction and area of the sky.

A high-sensitivity luxmeter Sonopan L-52 was used to measure the illuminance. This lux meter has four sensitivity ranges: 1–2000 lux, 0.1–200 lux, 0.01–20 lux and 0.001–2 lux. Only the last, most sensitive range was used in the measurements.

Measurement methodology

All measurements were made in points meeting the following conditions:

- lack of close terrain obstacles vignetting a part of the measured area of the sky (the measurement points were set so that these obstacles did not rise higher than 25° above the horizon plane);
- lack of close light sources whose light would fall directly into the measurement window of the meters (the measurement points were set so that these light sources did not rise higher than 10° above the horizon plane).

Taking measurements at some planned points was impossible, for example, because of them being of private property, the inability to enter at night or terrain obstacles (e.g. dense forest or cliffs).

As far as was possible, three types of measurements were made at the given test points:

- Measurements of the zenith surface brightness of the night sky
  At each measuring point, measurements of the brightness of the night sky were made using both SQM and SQM-L meters giving the results in mag·arcsec^{-2}

(hereinafter, the value measured in this way is referred to as S_a). Values expressed in these units can be, according to manufacturer's documentation, correlated with the luminance expressed in SI units (mcd·m^{-2}). Keep in mind that while the mcd·m^{-2} scale is linear and simple, the mag·arcsec^{-2} scale is logarithmic and inverse. This means that a higher value of S_a indicates a lower surface brightness of the night sky, with a difference of 1 mag·arcsec^{-2} representing a more than double (2.512 to be exact) change in the surface brightness of the night sky. The measurements were repeated each time until the result was stable with an accuracy of 0.01 mag·arcsec^{-2} for three consecutive readings. After recording the measurements, the average value was entered into the table, with the extreme values being rejected (Table 5.5).
In situations where the sky was dominated by heavy cloud cover, but a cloudless area was visible near the zenith, measurements were made with SQM-L gauges directed towards such area (measurements at Z6 and Z7 sites on the night of 16/17.10). In one case, when the measurement was made in very heavy rain conditions (C1 on the same night), it was repeated an hour later in slightly better weather conditions.

- Azimuth measurements of the surface brightness of the night sky
  The uniformly full cloud cover, especially with low *Stratus* and *Nimbostratus* clouds, created the possibility to research the impact of the distribution of terrestrial light sources on the brightness distribution of the night sky glow. In order to research this issue, the measurements were made with the SQM-L, inclined to the horizon at an angle of 45° in the four cardinal directions N, E, S and W. As in the previously discussed cases, the measurements were repeated each time until the displayed value was stable with an accuracy of 0.01 mag·arcsec^{-2} for three consecutive readings.
- Horizontal surface illuminance measurements.
  In the absence of terrain obstacles on the horizon exceeding the angular height of 10°, as well as in the case of full cloudiness of the entire sky, measurements of the horizontal surface illuminance were made at a height of 1.7 m above ground level. A high-sensitivity luxmeter Sonopan L-52 was used for the measurements. Continuous measurement was performed until the value shown on the luxmeter display stabilised at an accuracy level of 0.003 lx.

Measurement data

In the following tables are the values of the zenith surface brightness of the night sky (S_a) measured with the SQM and SQM-L meters, as well as the illuminance values of the horizontal surface (E) measured at the same time, both for the night of 15/16 October 2020 (Table 5.5.1) and 16/17 October 2020 (Table 5.5.2).

Table 5.6 presents the measured values of the surface brightness of the night sky (S_a) at a height of 45° above the horizon in the azimuths of the four cardinal directions of the horizon (N, E, S and W). Such measurements were made only when the sky was evenly covered with clouds of low and middle levels.

Table 5.5.1. List of measurements of the surface brightness of the night sky (S_a) at the zenith (SQM-L and SQM) and the illuminance of the horizontal surface (E) at a height of 1.7 m above the ground at night on 15/16 October 2020

Measuring point	S_a [mag·arcsec^{-2} (mcd·m^{-2})]		E [lx] ±0.003 lx	Notes on factors affecting the measured value
	SQM-L	SQM		
C1	19.89±0.08 (1.21±0.08)	20.26±0.07 (0.86±0.05)	0.015	–
C2	20.88±0.07 (0.48±0.03)	21.02±0.07 (0.43±0.03)	0.018	City glow 5° above the southern horizon (Lębork)
C3	20.89±0.01 (0.48±0.01)	21.11±0.10 (0.39±0.03)	–	–
C4	21.07±0.05 (0.41±0.02)	21.22±0.01 (0.36±0.00)	–	–
C5	20.49±0.01 (0.69±0.01)	20.46±0.44 (0.71±0.24)	0.011	Street lamps about 100 m to the east
C6	21.36±0.06 (0.31±0.02)	21.53±0.48 (0.27±0.10)	< 0.001	City glow 5° above the western horizon (Łeba)
C7	20.78±0.09 (0.53±0.04)	21.01±0.05 (0.28±0.13)	0.018	The bright glow of the city 10° above the western horizon (Łeba)
C8	21.00±0.04 (0.44±0.01)	21.28±0.13 (0.34±0.04)	–	The road between the trees The flashes of the Stilo lighthouse are visible on the northern horizon
Z1	19.43±0.11 (1.83±0.17)	19.55±0.08 (1.66±0.11)	0.008	Approx. 50 m from the illuminated road
Z2	20.01±0.02 (1.08±0.02)	19.98±0.30 (1.11±0.27)	0.039	Street lamp at a distance of about 30 m
Z3	18.95±0.10 (2.85±0.26)	19.29±0.25 (2.09±0.44)	0.016	Very brightly lit Żarnowiec power station at a distance of approx. 100 m
Z4	19.38±0.06 (1.93±0.10)	–	0.014	The shore of Żarnowiec Lake, behind a clump of trees; near the lamp, view only towards the east, at a distance of 30 m there is an illuminated marina
Z5	19.86±0.08 (1.24±0.09)	19.24±0.33 (2.20±0.58)	0.014	Broken clouds, visible stars in the gaps
Z6	20.46±0.06 (0.71±0.04)	20.51±0.01 (0.68±0.01)	0.015	–

Z7	19.90±0.08 (1.19±0.08)	19.98±0.08 (1.11±0.08)	0.016	–
Z8	20.45±0.07 (0.72±0.05)	20.44±0.06 (0.73±0.04)	0.019	No outdoor lighting; however, there are trees at a distance of approx. 30 m

Table 5.5.2. List of measurements of the surface brightness of the night sky (S_a) at the zenith (SQM-L and SQM) and the illuminance of the horizontal surface (E) at a height of 1.7 m above the ground at night on 16/17 October 2020

Measuring point	S_a [mag·arcsec^{-2} (mcd·m^{-2})]		E [lx] ±0.003 lx	Notes on factors affecting the measured value
	SQM-L	SQM		
C1	20.84±0.03 (0.50±0.01)	21.04±0.11 (0.42±0.04)	–	Moderate rain.
C2	21.24±0.01 (0.35±0.00)	21.55±0.05 (0.26±0.01)	< 0.001	Completely cloudless sky; Bortle scale: 3
C3	21.28±0.04 (0.33±0.01)	21.44±0.01 (0.29±0.00)	–	Completely cloudless sky; Bortle scale: 3; passing waves of fog
C4	21.17±0.01 (0.37±0.00)	21.24±0.01 (0.35±0.00)	–	Completely cloudless sky; Bortle scale: 3
C5	21.22±0.02 (0.35±0.01)	21.67±0.08 (0.23±0.02)	–	Variable cloudiness during the measurement
C6	21.20±0.02 (0.36±0.01)	21.33±0.01 (0.32±0.00)	< 0.001	A nearby forest in the field of view of the luxmeter
C7	21.25±0.05 (0.34±0.02)	21.56±0.13 (0.26±0.03)	< 0.001	Completely cloudless sky; Bortle scale: 3
C8	20.25±0.02 (0.86±0.01)	20.20±0.14 (0.91±0.11)	–	Completely cloudless sky; Bortle scale: 3
Z1	21.09±0.05 (0.40±0.02)	21.02±0.04 (0.43±0.01)	–	Clear at the zenith, about 30° from the zenith, intermittent clouds
Z2	20.69±0.12 (0.58±0.06)	20.43±0.59 (0.73±0.31)	< 0.001	–
Z2	20.70±0.01 (0.57±0.00)	20.23±0.36 (0.89±0.25)	< 0.001	Few cumulus clouds are visible around 40° from the zenith
Z3	18.60±0.02 (3.97±0.08)	18.54±0.18 (4.20±0.63)	< 0.001	Rain
Z4	18.99±0.02 (2.77±0.05)	19.13±0.04 (2.44±0.08)	–	–
Z5	20.70±0.09 (0.57±0.04)	20.64±0.08 (0.60±0.05)	–	Zenith gap in the clouds with a diameter of 30°
Z6	20.24±0.06 (0.87±0.05)	20.19±0.25 (0.91±0.19)	–	Zenith gap in the clouds with a diameter of 15°

Table 5.5.2 (cont.)

Z7	19.97±0.02 (1.12±0.02)	20.08±0.04 (1.01±0.04)	–	Heavy rain, measurements from the car
Z8	18.70±0.11 (3.59±0.33)	18.90±0.18 (3.01±0.45)	–	Brightly lit Żarnowiec power station at a distance of approx. 100 m Medium clouds, broken, 100% cloudiness at the zenith, darker patches about 30° from the zenith

Table. 5.6. Measurements of the surface brightness of the night sky (S_a) at a height of 45° above the horizon in the azimuths of the four cardinal directions of the horizon (performed only when the sky is evenly and fully clouded with low and middle clouds)

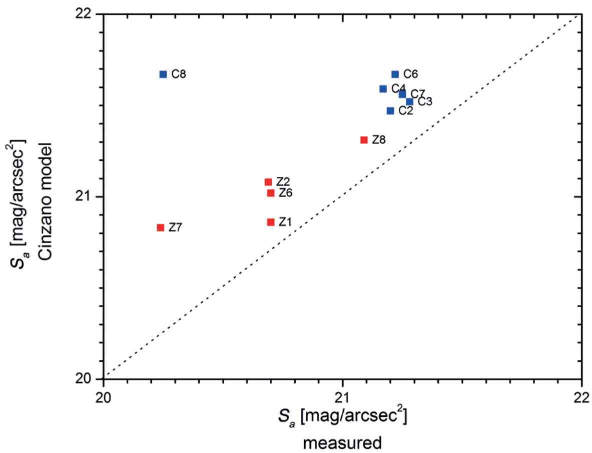
Measuring point	Direction on the horizon				Notes
	N	E	S	W	
Z3	19.71±0.10 (1.42±0.17)	19.59±0.10 (1.60±0.11)	18.63±0.10 (3.85±0.05)	18.30±0.10 (5.24±0.90)	Brightly lit Żarnowiec substation from the south-west
Z4	trees	19.81±0.30 (1.30±0.32)	harbour	trees	Dark horizon, without any lights (the other shore of the lake); however, 30 m to the south there is an illuminated yacht harbour
Z5	–	19.50±0.10 (1.73±0.15)	19.26±0.13 (2.15±0.24)	–	Dark eastern horizon, from the south-east a bright glow of light from a nearby city to the height of 5° above the horizon (Wejherowo)
Z6	20.42±0.10 (0.74±0.07)	20.04±0.10 (1.05±0.09)	19.88±0.10 (1.22±0.11)	20.01±0.10 (1.08±0.09)	Virtually the entire horizon is dark, only from the west, at a distance of 200 m, the walls of apartment blocks of a nearby town (Gniewino) are visible
Z7	19.77±0.10 (1.35±0.12)	19.59±0.10 (1.59±0.14)	19.96±0.10 (1.13±0.10)	20.03±0.10 (1.06±0.09)	Virtually the entire horizon is dark, only from the south visible single street lamps
C1	20.54±0.10 (0.66±0.06)	20.32±0.10 (0.81±0.07)	19.70±0.10 (1.44±0.13)	20.40±0.10 (0.75±0.07)	To the south, at a distance of approx. 0.5 km, street lamps are visible
C5	20.89±0.10 (0.48±0.04)	19.80±0.10 (1.31±0.12)	20.49±0.10 (0.69±0.06)	20.80±0.10 (0.52±0.05)	Generally dark surroundings, but from the east visible street lamps at a distance of approx. 100 m, otherwise visible glows of light from the surrounding cities: one in the south at a height of approx. 2° above the horizon (Lębork), the other in the west at a height of approx. 5° above the horizon (Łeba)

C6	21.42±0.10 (0.29±0.03)	21.55±0.10 (0.26±0.02)	trees	21.32±0.10 (0.32±0.03)	–
C2	trees	trees	20.53±0.10 (0.67±0.06)	20.43±0.10 (0.73±0.06)	–
C4	21.25±0.10 (0.34±0.03)	trees	trees	trees	–

Data analysis

Comparison of the measured values of S_a with the available data on the level of light pollution in the researched regions

Measurements of the surface brightness of the sky at the zenith (S_a) made in the conditions of a completely cloudless sky enabled comparison of the determined values with the values postulated by the Cinzano model (Falchi et al. 2016) (Ill. 5.13).



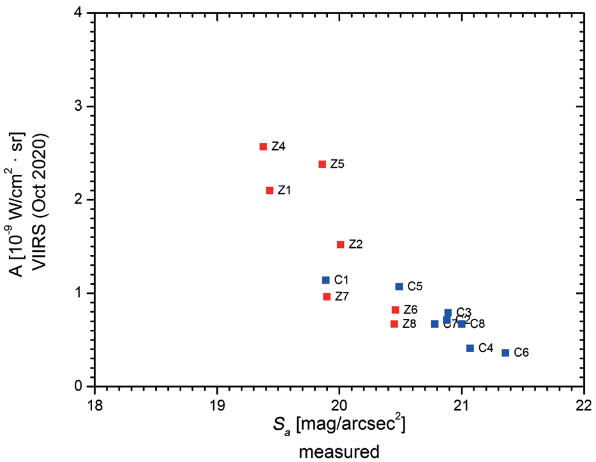
Ill. 5.13. S_a values resulting from the model (Falchi et al. 2016) compared to the measured values; measurement errors smaller than point sizes

It is clearly visible that for all measuring points where this comparison was possible, the measured values are lower than those suggested by the model, which means that at these points, the sky is significantly brighter than the model predictions. The reason for this may be that the model was made in 2015 – it should be expected that over the next five years, due to the progressing urbanisation, the lighting of the area with artificial light will probably increase. It is also possible that the Milky Way, visible at the zenith during measurements, is partly responsible for this effect.

There is a clear clustering of the values determined at the measurement points located in region C: C2, C3, C4, C6, C7 (the departure of point C8 results from the difficult measurement conditions within the tree-lined avenue). This means that in the central part of region C, the S_a value of cloudless sky can be assumed to be about 21.2–21.3 mag·arcsec^{-2} (0.33–0.36 mcd·m^{-2}). This value is consistent with the values previously determined in similar conditions in sparsely populated mountain areas (up to approx. 100 inhabitants·km^{-2}) (Ściężor 2018, Table 17, 132), which is consistent with the value determined for population density reported in the literature for the commune of Choczewo in which these measuring points are located (30 inhabitants·km^{-2}) (Polska w liczbach 2023a).

In the case of measurement points located in the region Z (Z1, Z2, Z6, Z7, Z8) the clustering that might result from model map analysis (Falchi et al. 2016) is not observed. The observed spread of S_a, 20.2–21.1 mag·arcsec^{-2} (0.40–0.91 mcd·m^{-2}) should be associated with more nearby ground light pollution sources. The average value of the measured zenithal S_a is about 20.7 mag·arcsec^{-2} (0.57 mcd·m^{-2}), which corresponds to a population density of about 300 inhabitants·km^{-2}. For the municipality of Krokowa (where the discussed points are located), the population density is 51 inhabitants·km^{-2} (Polska w liczbach 2023b), which does not explain such a high brightness of the night sky. The observations made during the measurements show that in this area, there is a significantly greater number of street lamps and illuminated objects (e.g. the Żarnowiec power substation).

In order to determine the impact of ground light sources on the brightness of the night sky, measurements made under full cloud cover were used. In such a case, low clouds act as a screen, the local brightness of which is related to the local radiance from the earth's surface (Ściężor 2018, 156). Radiance is measured by satellite using the VIIRS camera mounted on the Suomi NPP satellite (https://jointmission.gsfc.nasa.gov/). This enabled a graphical comparison of these values (Ill. 5.14).



Ill. 5.14. Comparison of the radiance emitted into space from the measurement points in October, 2020 with the measured S_a values at these points; measurement errors smaller than point sizes

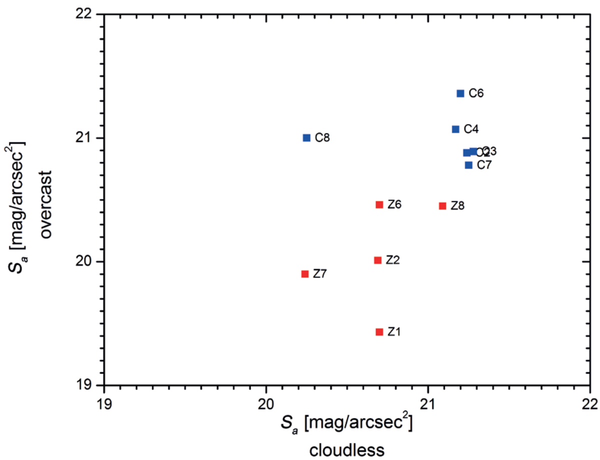
The radiance determined at the measurement points in region C does not exceed 1.3×10^{-9} W·cm^{-2}·sr^{-1} and indeed the average surface brightness of a fully clouded sky is the lowest in this region (about $S_a = 21$ mag·arcsec^{-2}, i.e. 0.43 mcd·m^{-2}). A similar situation is visible in the peripheral points Z2, Z6 and Z8 in the region Z.

In the case of the other, central points of the region Z (Z1, Z3, Z4, Z5), the satellite-measured radiance is in the range of $(2–3)\times10^{-9}$ W·cm^{-2}·sr^{-1}, which corresponds to the measured S_a value in the range of 19 to 20 mag·arcsec^{-2} (1.09–2.74 mcd·m^{-2}).

Description of the light pollution of the researched regions based on the measurement data

Classification of measurement points in terms of the level of light pollution

In order to isolate possible clusters of measurement points with a similar degree of light pollution, those points were selected for which in the following two measurement nights, there was both a completely cloudless sky and a fully overcast sky with low-level clouds. These are Z1, Z2, Z5, Z7, Z8 (region Z) and C6, C2, C3, C4, C7, C8 (region C). A cluster diagram was made, showing the dependence of S_a measured in cloudless sky conditions on the same value measured under full cloud cover (Ill. 5.15).

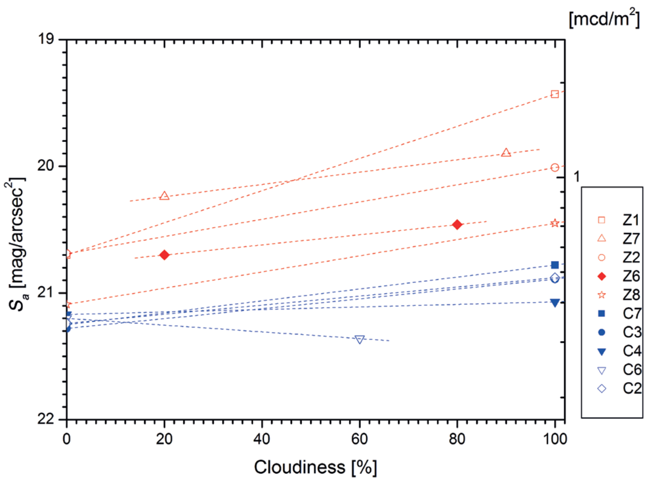


Ill. 5.15. The dependence of S_a measured in cloudless sky conditions on the same value measured in completely cloudy sky conditions. Measurement errors are smaller than the point sizes

While in both regions, S_a, measured with cloudless sky, is similar and is in the range of 20.2 to 21.3 mag·arcsec^{-2} (0.33–0.91 mcd·m^{-2}), clear stratification occurs in the overcast sky between clusters of points from the researched regions. It is clear that in full cloud cover, the value of S_a measured in region C is significantly higher than in region Z (remembering that the S_a scale is the inverse scale, it means that the cloudless sky is significantly darker in region C). This is related to the nature of light scattering in the atmosphere (Ściężor 2020). Low clouds reflect local lighting, while in the case of a cloudless sky, distant urban centres become the source of the brightening of the sky. This means that in both regions, the level of distant lighting (from distant, larger cities, like Łeba, Lębork, Wejherowo) is similar, while region Z is more susceptible to the impact of local lighting (mainly street lamps).

Estimation of the level of light pollution

One of the methods of determining the level of light pollution in the examined area is to determine the dependence of S_a on cloud cover. This was possible for a number of tested measurement points (Ill. 5.16).



Ill. 5.16. Dependence of the measured S_a value on the degree of cloud cover; measurement errors smaller than point sizes

As in the case of the previous analyses, there is a clear division of the measurement points into those located in region C and in region Z. Points C2, C3, C7 show practically identical characteristics, which means that the nature of light pollution in this aregion is very similar. Points C4, and especially C6, differ from this cluster, where there is a practical (and in the case of C6 complete) lack of terrestrial light sources brightening the zenith. It is worth noting that in point C6, so far only for the second time in Poland (the first case is the southern Bieszczady Mountains (Ściężor 2018, 131-132)), an example of the opposite characteristic was found, i.e. a situation where the brightness of the sky decreases when the cloud cover increases. In the case of points in region Z, despite the significantly higher surface brightness of the sky, the described characteristics are similar to those in region C, which means that the illumination of the sky by terrestrial sources is similar. The exception here is point Z1, where the nearby cities (Wejherowo, Władysławowo and Puck) undoubtedly have a significant impact.

Summary and Conclusions

When analysing the obtained measurement results, it should be remembered that for technical reasons, they were one-off and therefore characterised by a certain degree of randomness. There is no certainty that the conditions were representative or that the obtained value for the reference (cloudless) sky is the most accurate description of the night sky in the studied locations. Even in reference conditions (astronomical night, without clouds and moon), the measurements differ from each other (Ściężor 2018). However, measurements within the indicated regions showed a significant difference in the level of light pollution between region C and region Z.

The average measured zenith S_a value for a cloudless sky in region C is equal to 21.23 mag·arcsec^{-2} (0.35 mcd·m^{-2}), while in Z: 20.83 mag·arcsec^{-2} (0.51 mcd·m^{-2}). This means that the surface brightness of a cloudless sky in region Z is nearly one and a half times higher than in region C. The S_a value measured in region C with the wide-angle SQM is almost always higher than this one measured with the narrow-angle SQM-L. It can be related to the lack of distant, bright sources of sky glow that brighten the cloudless sky in the non-zenithal areas. In the region Z, the opposite effect was observed. This effect as well as the increased brightness of the cloudless sky in region Z are probably due to the proximity of large urban centres, first of all, Władysławowo and Wejherowo.

In the case of a completely overcast sky, these values are respectively 20.71 mag·arcsec^{-2} (0.57 mcd·m^{-2}) and 19.51 mag·arcsec^{-2} (1.71 mcd·m^{-2}). This means that the surface brightness of the overcast sky in region Z is exactly three times higher than in region C. In both regions, the SQM-L values are usually lower than the SQM values. Both phenomena can be explained by a dense network of brightly lit roads as well as small but brightly lit villages, especially in the region Z.

As expected, a positive correlation was found between the surface brightness or luminance of the night sky and the radiance determined by satellite (Table 5.4). However, there is no close relationship between these quantities (Ill. 5.14), which does not allow the treating of radiance as a simple indicator of light pollution – such treatment of radiance is sometimes found in the literature on the subject.

In region C, the main sources of the cloudless night sky glow are the cities of Łeba and Lębork, but they contribute less to this factor than Wejherowo in region Z. The significant part of region C is forested, the settlement is sparse, in particular, the northern part of the region, adjacent to the unlit sea, is additionally covered by a coastal forest, which explains the lower night sky glow brightness in this region.

Undoubtedly, region C better preserves the natural night environment. Region Z is already significantly degraded in terms of the natural night environment. However, as mentioned earlier, the south-western shore of Żarnowieckie Lake (located in region Z) has been classified as the Natura 2000 Area Opalińskie Buczyny, and the Żarnowieckie Lake gutter is an ecological corridor of supra-regional importance.

Taking into account the previously published categorisation of light-polluted areas in Poland (Ściężor 2013), region C can be classified as category “C”, while region Z only as category “B”. The decision to build a nuclear power plant in region C, which also includes a number of protected areas, is all the more worrying. Moreover, the investment area is located far from local radiance centres (Ill. 5.11), which means that both the zenith sky brightness predicted by the model (Ill. 5.12, Table 5.4: S_a = 21.7 mag·arcsec^{-2}) and the determined during measurements (S_a = 21.4 mag·arcsec^{-2}) (Table 5.1) (point C6) places it among the best preserved night areas in Poland (Ill. 5.17). The planned investment will certainly disrupt this system. Verification measurements in this area are planned both in the coming years, during the implementation of the investment, and after its completion in the twenty-thirtiess. Undoubtedly, they will answer the question of how the nuclear power plant complex will affect this specific aspect of the natural environment, which is primeval night darkness.

Ill. 5.17. Night, cloudless sky at measurement point C7 (night 16/17.10.2020), just 1.5 km from the southern border of the investment area (photo: T. Ściężor)

Acknowledgments

We would like to thank Bogdan Siedlecki for the necessary help in making so many measurements in such a large space in such a short time.

6. A night sky light pollution monitoring network in Toruń, Poland – experience from the first year of operation and assumptions for the future

Dominika Karpińska*
Mieczysław Kunz**

Modern man transforms the environment to a far greater extent than ever before in history. This process has greatly accelerated in the first two decades of the twenty-first century. Transformations are accompanied by extremely large-scale emissions of various types of pollutants, not only to soil or water but also to the atmosphere (Qadri et al. 2020; Wani et al. 2020; Wang et al. 2004). Changes in the quality of the environment, the direction and intensity of negative transformations have become one of the main reasons for the search for new and more efficient research methods as well as recording and surveillance systems. It is necessary to increase interest in comprehensive monitoring systems for key environmental parameters and to strengthen the impact and role of targeted education and the development of environmental awareness.

The monitoring of selected environmental parameters can be performed in several ways, whether at the local, regional or global level. Regardless of the level chosen, it is usually an interdisciplinary process and, thanks to technological advances, it is becoming increasingly automated. Targeted monitoring enables a more effective comprehension of the harmful process of environmental degradation, its course over time, spatial distribution in the different dimensions, and impact on ecosystems as well as on the life and health of living organisms and, above all, on humans themselves. A multifaceted understanding of the observed phenomenon will enable more effective countermeasures to be taken in the future and effective mechanisms to be developed to reduce or eliminate its negative impact.

The analysed phenomenon is an example of one of the environmental pollutants of anthropogenic origin, which is becoming increasingly noticeable and widespread. It has been addressed with increasing frequency and research in this area is being

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conducted by a growing group of scientists from many countries around the world (Karpińska & Kunz 2019, Kołomański et al. 2019, Kyba et al. 2015a, Kyba et al. 2015b, Pun & So 2012, Ściężor 2021).

This chapter presents the experience to date with the operation of an automatic network monitoring the light pollution of the night sky in Toruń. The main element of the system are compact recording devices of our own construction deployed within the administrative boundaries of the city. In Toruń, measurements of the surface brightness of the night sky with the use of hand-held SQM-L measuring devices have already been performed since 2017, while the construction of the network for monitoring this phenomenon, based on remote data transmission to a designated server using LoRa technology (Semtech 2015, Turčinović et al. 2020), began in 2020. The system has been operational for more than a year and is being expanded with new measuring stations, with systematic data acquisition being conducted on a continuous basis.

1Area covered by the automatic monitoring of the night sky

An interdisciplinary team consisting of staff from the Faculty of Earth Sciences and Spatial Management and the Faculty of Physics, Astronomy and Informatics at Nicolaus Copernicus University in Toruń has been established to perform works and operations related to the design of the night-sky monitoring system. The team includes specialists in environmental monitoring, geoinformation and geoinformatics, automation and measuring systems. Toruń, which is located in the central part of the Kujawy-Pomerania Province, was selected as the site for the long-term testing of the monitoring network. It is an attractive tourist attraction, a medieval city with a population of about 180,000 (City of Toruń n.d.), which covers an area of less than 116 km^2.

Toruń is an example of a medium-sized agglomeration with all the characteristic types of development within its administrative boundaries, where we can find, among other features, high- and medium-rise multifamily residential buildings, compact housing developments in the city centre, stand-alone houses, industrial and commercial facilities as well as numerous green areas and non-urbanised areas. For the sake of municipal operations, the city has been divided into twenty-four neighbourhoods (housing estates) and each of the above-mentioned housing types dominates in specific parts of the city, as does the type and density of installed outdoor lighting infrastructure. An important element of the city's landscape is the Vistula River, which divides the city into two parts, as well as an altitude difference of more than 35 m between its lowest and highest areas. The existing high and compact urban development, dense and mature forest stands as well as the terrain elevation affect the spatial range of the public LoRa network selected for communication between devices. When determining the location of all components of the monitoring systems, it was necessary to perform selected field experiments on signal quality, visibility and propagation, and to determine all other relevant measurement and access parameters.

2Measurement of light pollution of the night sky in Toruń

The phenomenon of light pollution of the night sky can be measured using various research methods, which have been described in detail in the available literature. They can be divided according to specific criteria, e.g. according to the tools used, into instrumental methods and observational methods, or according to the complexity of the measurement process, into methods that can only be used by a qualified operator or a non-professional (Jechow et al. 2017a, Hänel 2017, Kyba et al 2015a, Pun and So 2012, Ściężor 2021). However, the most frequently used measurement methods are registrations with the use of photometers and digital cameras, mainly of the “fish-eye” type (Jechow et al. 2017a, Jechow et al. 2019, Kołomański 2019, Kyba et al. 2015b, Pun and So 2012, Ściężor 2021). Measurements made in this way make it possible to compare the intensity of the phenomenon recorded at different locations (Kyba et al. 2015b, Pun et al. 2014). In some research centres, studies using satellite imagery or aerial photographs are also used. The most commonly processed images are those taken by the Suomi NPP satellite with the VIIRS instrument, the DMSP satellite with the OLS instrument and the Luojia 1-01 satellites (Elvidge et al. 2013, Wang et al. 2020).

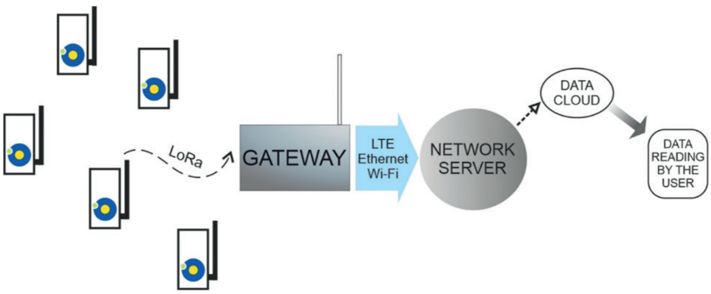
Measurement of the surface brightness of the night sky using SQM instruments

The first measurements of the surface brightness of the night sky in Toruń were made in mid-2017 and continued over the following twelve months. Repeated at regular intervals, the observations were performed using a hand-held SQM-L photometer from the Canadian company Unihedron, with the aim of determining the magnitude and spatial extent of the phenomenon in the city (Cinzano 2007). Following an analysis of accessibility and land cover/use, the monitoring network was established throughout the city, consisting of twenty-four stations. The results of the measurements were presented both in a tabular and spatial form using statistical and interpolation methods as well as visualisation tools available in GIS systems (Karpińska & Kunz 2019). An important element of the work was also to relate the obtained results to the distinguished urban development types and land cover categories as well as to the meteorological seasons of observation (Karpińska & Kunz 2020).

The work performed and the results obtained have helped to plan further targeted research into the phenomenon of the night sky light pollution in Toruń. The observations made, the diagnosed conditions and the limitations encountered when conducting the measurements were taken into account. The time-consuming and costly nature of night-time measurements was an indication and impulse for the development of an alternative research method based on the automation of the process of recording and data acquisition.

Automatic light pollution monitoring network

To advance research on light pollution at night in urban spaces, the automatic monitoring network has been set up. The network being developed consists of access gateways redirecting data to a server and devices of our own design (Ill. 6.1), measuring the surface brightness of the night sky with characteristics similar to a commercially available SQM photometer (Table 6.1; Karpińska & Kunz 2022a). The *magnitude per square arcsec* (mag·arcsec^{-2}), which is based on an inverse and logarithmic scale, was selected as the measurement unit used to present the results of the observations. When analysing the results, it is important to bear in mind that lower values represent a more light-polluted sky, while higher values show a darker sky. The instrument is mobile, compact and measurements are performed automatically. An important feature of the field-deployed kits is their energy efficiency, allowing at least nine months of repeated observations on a single power set.



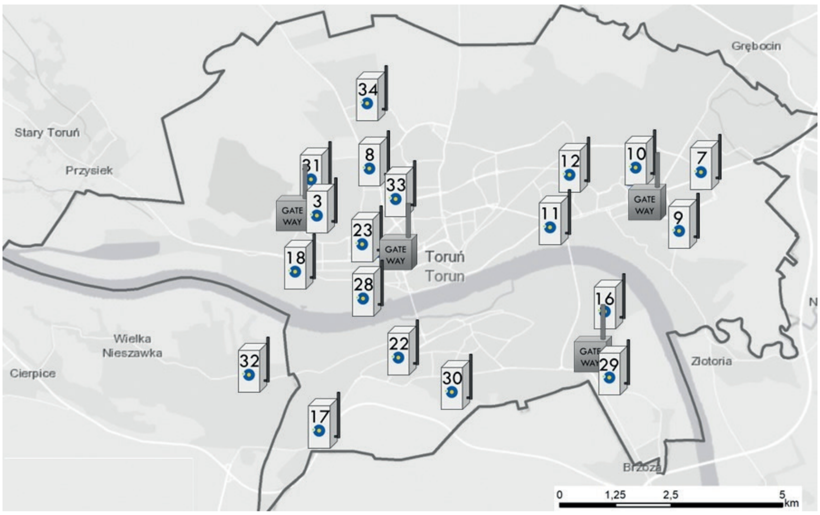
Ill. 6.1. Schematic diagram of the monitoring system. Source: own elaboration

In the established monitoring network, data transmission is based on the use of LoRa communication technology modules, which allow long-distance data transfer in the low-power mode (Semtech 2015, Turčinović et al. 2020). The established network is also characterised by a low cost of operation due to the fact that there are no licence fees, and by the ease and speed of data acquisition. All of the above features fit the selected solution into the modern concept of a smart city and the premises of the Industry 4.0 strategy (Mikhaylov et al. 2018, Turčinović et al. 2020). Field tests and experiments were performed to verify the correct operation of the measurement sets and the monitoring network itself (Karpińska & Kunz 2021, 2022a).

The first devices of the night sky light pollution monitoring network in Toruń were installed in June 2020. By mid-2022, a total of nineteen measuring stations and four access gateways (two using an internal version for external transmission and two completely external ones) were fully operational in the city (Ill. 6.2). The assigned number of the device is not its serial number, but its designation. In addition, during the creation of the network, the device was sometimes replaced due to an unexpected error. Such devices are assigned the same location and their working times complement each other. During the selection of each location for the stations, it was necessary to check important factors such as the usability of the selected site in terms of the data source, the possibility of easy installation, the safety of the device against unauthorised access, the proximity of street lamps or other illuminated elements and the availability of the LoRaWAN network.

Table 6.1. Main technical parameters of the system of our own construction to measure the surface brightness of the night sky

Parameter	Characteristic
Weight	380 g
Dimension	5.5×8.2×15.8 cm
Standard of data transmission	LoRaWAN
Frequency bands	868 MHz
Operating time [3 000 mAh]	~ 9 month
Range in built-up areas	3-4 km
Number of measurements during the day	36
Frequency of measurements	15 min
Operational time	21:00-06:00 CEST
Measuring sensors	surface brightness of the sky, temperature, humidity
Spectral characteristics	similar to the human eye
Angle of data collection	27°
Tightness class	IP65

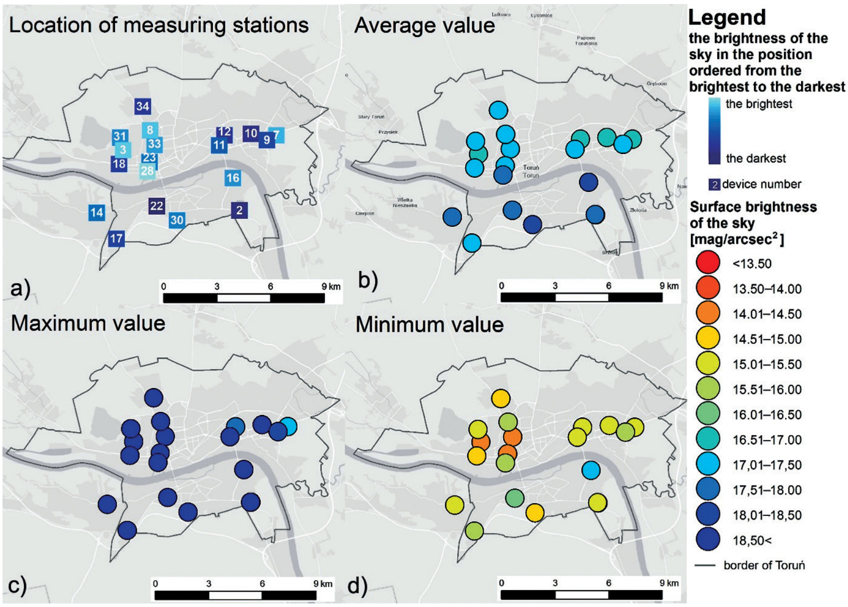


Ill. 6.2. Location of measurement stations in Toruń and access gateways in the established network of urban monitoring. Source: own elaboration

Results of the conducted measurements

Since mid-2020, the systematic and automatic monitoring of the light pollution of the night sky has been performed in Toruń, initially based on three stations previously used at the technology demonstration stage. Since then, further locations have been added to the city map, gradually increasing the monitored area (Ill. 6.3a). Ultimately, the monitoring network will consist of approximately forty sites for optimum coverage (Karpińska & Kunz 2022b).

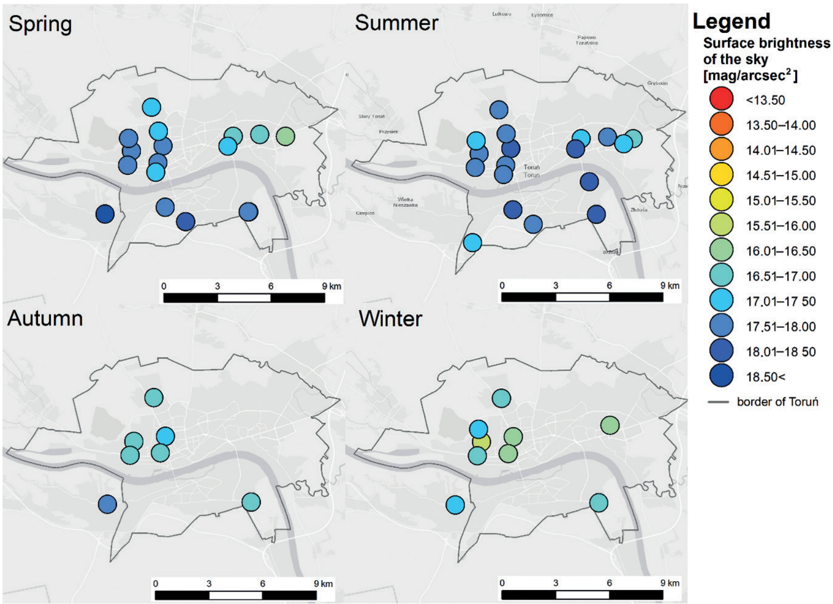
The data collected so far in all measurement conditions already allows selected analyses to be conducted and various statistics to be compiled (Ill. 6.3 & 6.4). Ill. 6.3a shows the average annual value of the night sky surface brightness measurements at each measurement location relative to the classification of the locations from the brightest to the darkest.



Ill. 6.3. Visualisation of the measured values for each measurement station: a) location of the stations and the average value presented on a scale from the smallest to the largest, b) average annual value calculated for all meteorological conditions, c) maximum measured value, d) minimum measured value. Source: own elaboration

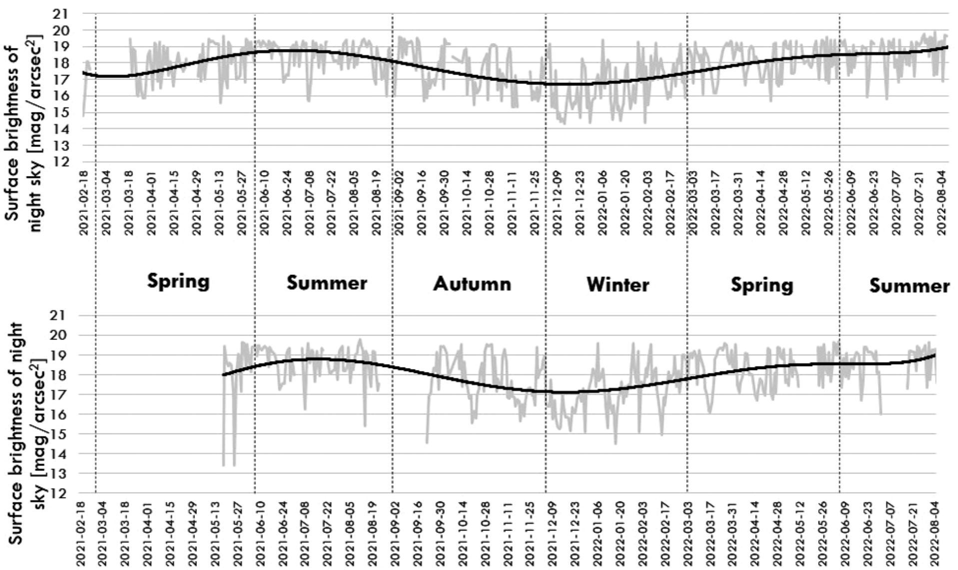
Analysis of the average measured values (6.3b) shows that the darkest areas (dark blue colour) are located mainly on the outskirts of the city; more light pollution was recorded in the city centre. Larger residential areas, with a greater accumulation of outdoor lighting infrastructure, mainly street lamps, were characterised by the highest brightness. Ill. 6.3c and 6.3d show the minimum and maximum values of the brightness of the night sky. The maximum values are relatively consistent, while the minimum values show large differences for each location. The brightest readings are located in the very centre of the city and were recorded on cloudy nights, when the light emitted from the ground was reflected by the clouds (Jechow et al. 2017b, Kocifaj 2007, Ściężor 2020).

The seasonal variability is also perfectly illustrated by the graphs calculated for all meteorological conditions of the measured sky surface brightness recorded at the two longest-operating monitoring sites (Ill. 6.5). The upper graph shows measurements taken by device No. 3, while the lower graph shows measurements taken by device No. 29. In both cases, the trend line was added during the analysis, which follows a similar pattern for each device. In summer, the measured values are higher, corresponding to a darker sky, while in winter, the values are much lower, corresponding to a brighter night sky. The data thus represented confirms the results of the analysis presented in Ill. 6.4.



Ill. 6.4. Average surface brightness of the sky in particular seasons. Source: own elaboration

The results for each measurement station are also presented in a tabular form. Table 6.2 shows the averages of the night sky brightness for each season and the maximum and minimum values, including the smallest and highest values for each measurement station operating within the monitoring network of the city of Toruń. In addition, a colour gradient was applied to the value field, whereby the red background indicates the brightest, most light-polluted sky, while the blue background indicates the darkest values and the least polluted night sky. The results also show which station recorded the highest and which the lowest value of surface brightness of the night sky. The results of the annual summary are in line with the results presented in Ill. 6.3.



Ill. 6.5. Over one year of measurements from two devices – 3 (top) and 29 (bottom) located in Toruń. Source: own elaboration

Tab. 6.2. Example of a compilation of average, maximum and minimum values of surface brightness of the sky for each measurement station from one full year of recording, broken down into the adopted periods of analysis

	Spring			Summer			Autumn			Winter			AllYear		
	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max	Av.	Min	Max
1	17.49	16.09	19.66										17.49	16.09	19.66
2	17.51	15.5	19.65										17.51	15.50	19.65
3	17.56	15.59	19.6	17.97	15.42	19.9	16.8	15.07	19.63	15.9	14.3	19.45	16.77	14.30	19.90
7	16.36	15.09	17.19	16.86	15.59	17.25							16.58	15.09	17.25
8	17.25	15.57	19.22	17.79	16.3	19.14							16.71	15.57	19.22
9				17.33	15.89	18.33							17.33	15.89	18.33
10	16.87	15.21	18.39	17.67	15.88	18.75				16.44	15.61	17.44	16.88	15.21	18.75
11	17.06	15.29	19.33	18.04	16.11	19.34							17.44	15.29	19.34
12	16.78	15.66	17.42	17.16	15.18	17.99							16.95	15.18	17.99
14	17.88	17.21	19.31	17.98	17.02	18.90							17.93	17.02	19.31
16				18.50	17.10	20.30							18.50	17.10	20.30
17				17.39	15.89	19.44							17.39	15.89	19.44
18	17.67	16.70	20.06	17.90	16.28	19.73	16.66	15.74	17.99	16.6	14.68	18.66	17.06	14.68	20.06
22	17.70	16.54	19.26	18.20	16.45	20.04							16.8	16.45	20.04
23	17.65	15.98	19.04	17.90	15.92	19.62	16.98	15.46	18.81	16.38	14.36	18.96	17.06	14.36	19.62
25	17.05	15.15	19.76	17.69	15.26	19.68	16.67	14.2	20.50	16.1	14.65	18.25	16.73	14.20	20.5
28	17.37	15.64	19.24	17.90	15.90	19.96							17.6	15.64	19.96
29	17.17	13.39	19.65	18.24	15.39	19.85	16.98	14.62	19.79	16.63	14.74	19.64	17.12	13.39	19.85
30	18.05	16.57	19.83	17.97	14.81	20.03							18.01	14.81	20.03
31	17.51	15.70	19.48	17.40	15.24	19.83	17.11	15.63	19.11				17.33	15.24	19.83
32	18.59	16.90	20.91				17.62	16.14	19.55	17.16	15.27	18.49	17.64	15.27	20.91
33	17.71	16.15	20.17	18.01	15.49	20.51	17.24	15.24	19.29	16.46	14.50	19.13	17.19	14.50	20.51
34	17.45	16.28	18.79	17.52	16.06	18.83	16.77	15.04	18.63	16.61	14.98	18.64	17.02	14.98	18.83

Conclusions and future of the project

Monitoring of the natural environment is a statutory function of specialised field institutions established by state authorities, as well as selected local government authorities performing their statutory tasks. This process should also be supported by research teams which, while collecting or analysing data, try to investigate the mechanisms, conditions and effects of the observed processes. It is advisable to register a wide range of environmental parameters, especially those that directly affect human health, functioning and life and are responsible for the deteriorating state of the environment. To gain a better understanding of all the interactions taking place at the human–environment interface, targeted measures are required, including investment in recording equipment and measurement kits. This will allow a more comprehensive determination of the current state, extent and intensity of the main factors, mainly those of anthropogenic origin and degrading the environment, as well as forecasting the direction and rate of changes.

The issues described in this chapter concerning the monitoring of the surface brightness of the night sky are gradually becoming the subject of interdisciplinary research by several national research units and dispersed research groups around the world. These efforts are aimed both at determining the causes of occurrence, mapping the extent or developing measurement methods, as well as at understanding the consequences and effects of light pollution on all living organisms, including humans. One of the directions of development in this area is work aimed at targeted, systematic and automatic monitoring of this phenomenon. The chapter presents the structure of the night-sky light pollution monitoring system consisting of dozens of measurement devices of our own design. The presented analyses prove the seasonal variability of the surface brightness of the night sky over the urbanised area. The highest measured value is observed in the city centre, in the most densely populated places. Areas far from large housing estates show less light pollution. The constructed recorder for measuring the surface brightness of the night sky operates in a distributed measurement structure, interconnected by the LoRaWAN network, which is a promising alternative to commercial solutions, especially in the case of urban areas.

The monitoring network established in the city of Toruń has successfully passed all the stipulated tests, including measurement, correct operation, communication and data archiving. The recorded and processed measurement data were analysed in various layouts and configurations, including the division into observation sessions of varying duration. This made it possible to present the problem of light smog in terms of both annual and seasonal variability, as well as in a horizontal gradient within the city limits. The measured values are also fully comparable with respect to the measurements by commercially available, factory-made SQM photometers. As a result, it is possible to compare the values with results obtained for other areas of the world. As part of the development of the night sky monitoring system built in Toruń, further stages are planned and mainly aimed at increasing the spatial range of the network – launching new devices and adapting them for other projects related to the acquisition of environmental data. The open-ended design of the system provides for the possibility of extending it with other sensors (e.g. for particulates of different sizes, ozone or noise) and adapting it to record further environmental parameters. This adds new possibilities for the described project to develop towards the comprehensive monitoring of environmental parameters. There is also the prospect of a personalised configuration of the system for new tasks that may arise during use and result from technical and technological advances, as well as the expectations of the institutions concerned.

7. The first results of light pollution measurements in the Transcarpathian Dark-Sky Park

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Nataliya Kablak**
Oleksandr Reity***
Pavlo Guranich****
Anatoliy Susla****

Transcarpathian Dark-Sky Park

On 11 June 2016, founding memorandum of the Transcarpathian Dark-Sky Park was signed in the Chorni Mlaky tract (Kniahynia village, Uzhhorod district).

The Transcarpathian Dark-Sky Park (with an area of 46,302 ha) includes the territory of the Uzhansky National Nature Park (39,159 ha) and selected areas in the cadastral area of the villages of Sukhyi, Tykhyi, Husnyi, Lyuta, Ruskyi Mochar and part of the village of Velykyi Bereznyi (see Ill. 7.1).

The Transcarpathian Dark-Sky Park was created in order to inform the general public and experts in the field of astronomy about the problems of light pollution of the night environment and environmental protection. The park area allows everyone to conduct astronomical observations on its territory, due to significantly lowered skyglow levels, promotes astronomy among children and the youth, and promotes the development of astrotourism in the Transcarpathian region.

On the occasion of the 150th anniversary of the fall of the Knyahynia meteorite in 2016, the East Carpathian Dark-Sky Tripark was proclaimed, which became the first in the world to be located on the territory of three states. The East Carpathian Dark-Sky Tripark (area 208,667 ha) includes the territory of the Dark-Sky Park Poloniny in Slovakia (48,519 ha), Bieszczady Starry Sky Park in Poland (113,846 ha) and the Transcarpathian Dark-Sky Park in Ukraine (46,302 ha).

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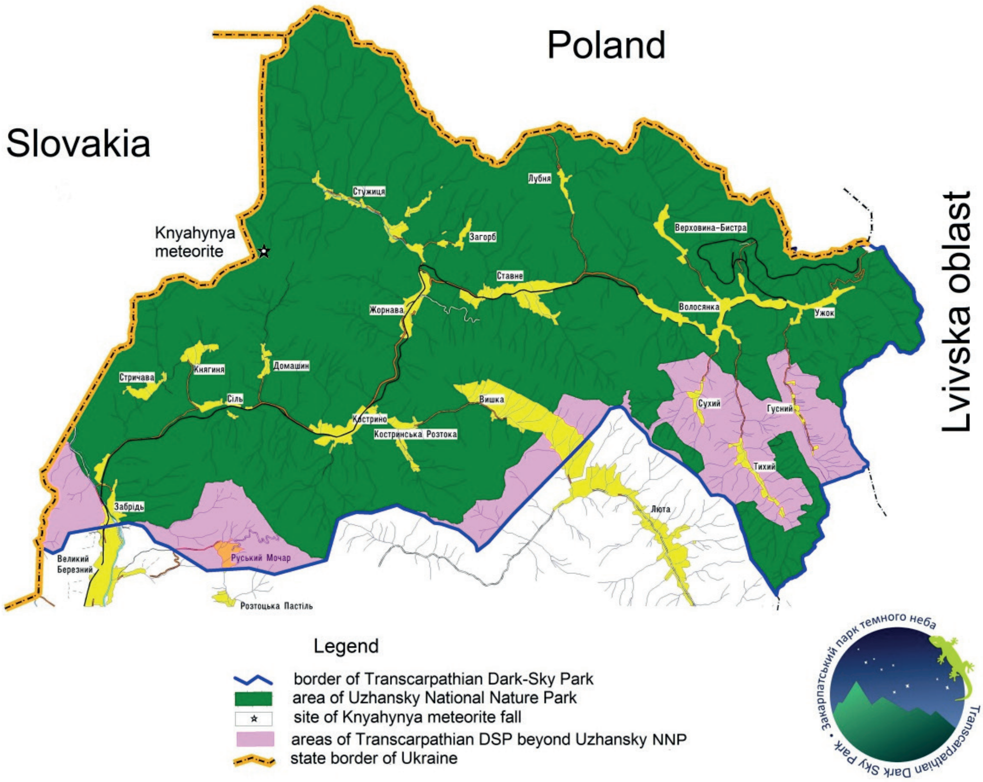
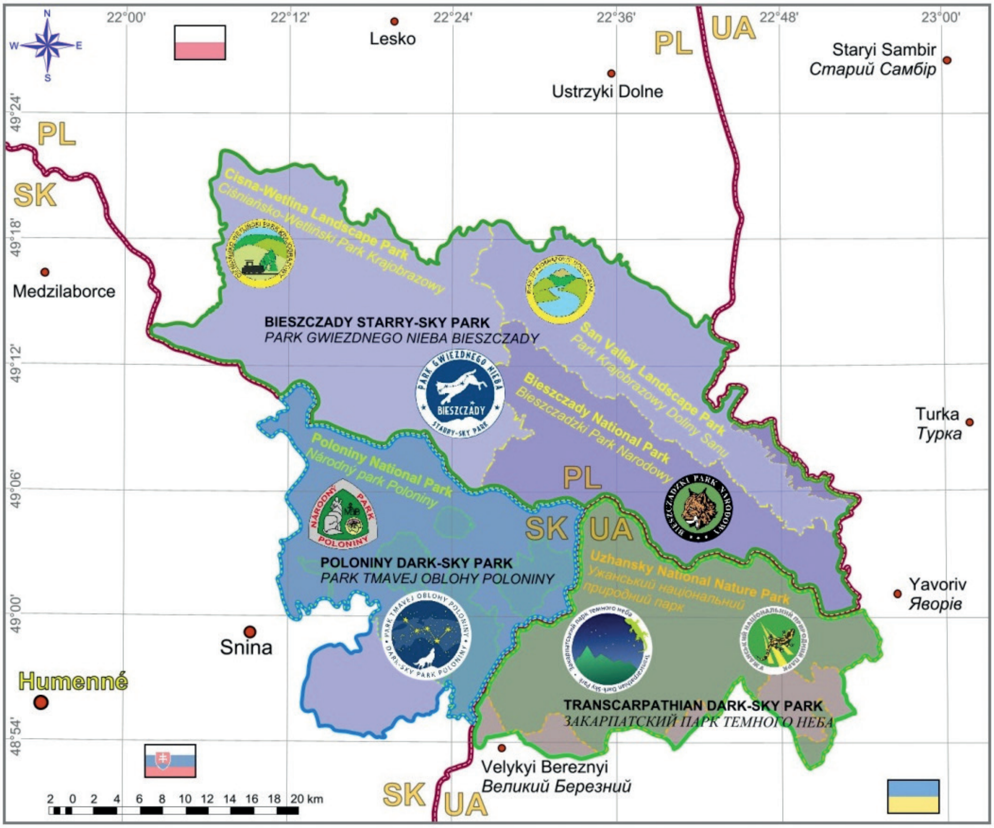


Ill. 7.1. Transcarpathian Dark-Sky Park. Flags – places where measurements of night sky brightness were performed (CSS 2021)

Due to the unique natural and cultural heritage sites included in the UNESCO international lists, the convenient location near the borders of the European Union and the lack of sources of environmental pollution (due to low population density, lack of production and industries), the border region is extremely attractive for eco-tourism. The creation of the Transcarpathian Dark-Sky Park has provided an opportunity to offer a new direction of tourism, bringing novelty to the tourist market.

In addition to good infrastructure, one of the most important factors for the development of astrotourism in the region is the quality of the night sky. The natural night sky is our common and universal heritage, but it is quickly becoming unknown to new generations. An important part of solving the problem of light pollution and understanding the quality of the night sky is to measure the brightness of the night sky (Nazarenko & Chernets 2014). Such measurements were performed at various points in the Transcarpathian Dark-Sky Park, resulting in the selection of locations, which combine rich natural heritage, historical past and most importantly, excellent night sky quality.



Ill. 7.2. East Carpathian Dark-Sky Tripark (CSS 2021)

Analysis of light pollution of the night sky in the Transcarpathian Dark-Sky Park

All measurements were performed using a SQM-LU-DL (Unihedron n.d.) device (Sky Quality Meter with narrow Field-of-View – lens, USB connectivity – data-logging). The main task for which SQM-LU-DL was purchased was measuring the night sky brightness in the Transcarpathian Dark-Sky Park.

One of the goals of the project was to start the process of registration of the Transcarpathian Dark-Sky Park in the International Dark-Sky Association (IDA). For this reason, measurements of the night sky brightness within the Transcarpathian Dark-Sky Park were performed according to the instructions provided by IDA. All measurements were conducted on nights around the new moon.

We conducted measurements in different places of the Transcarpathian Dark-Sky Park. In order to ensure that our values were not false, we conducted at least three nights (from evening to morning) of measurements in all these places and chose the average of the maximum achieved values in each night. All measurements was made at the zenith, and were taken in months when the Milky Way is near the zenith, this means that the obtained values are brighter than the real darkest conditions. All measurements are listed in Table 7.1.

Measured places:

1. Village Lubnya (coordinates where measurements were made: 49°02′09.2″N 22°43′05.9″E, maximum value of the night sky brightness – 21.91 mag·arcsec^{-2}, measurement dates: August 9–15, 2021) – is a village in Uzhhorod district of the Zakarpattia region. The population is 212 people. The village is located in the valley of the Lubnya river. The village is located in the northern most mountainous part of the district. It is located 42 km from the district centre, near the border with Poland, 7 km from the Stavne railway station.
2. Village Knyahynya (coordinates where measurements were made: 48°58′28.9″N 22°30′47.5″E, maximum value of the night sky brightness – 21.62 mag·arcsec^{-2}, measurement dates: August 9–15, 2021) – is a village in Uzhhorod district of the Zakarpattia region. The population is 319 people (2001).
3. Village Uzhok (coordinates where measurements were made: 49°00′07.4″N 22°53′14.96″E, maximum night sky brightness value – 21.68 mag·arcsec^{-2}, measurement dates: September 8–10, 2021) – is the village located under the Uzhotsky Pass, where the river Uzh originates and where the Transcarpathian region begins. The population of Uzhok as of 2011 is 722 people.
4. Village Vyshka (coordinates where measurements were made: 48°55′29.7″N 22°40′14.9″E, maximum value of night sky brightness – 21.50 mag·arcsec^{-2}, dates of measurements: October 8–11, 2021) – is the village located in a mountainous area in the valley of the Uzh river, 25 km from the district centre – Velykyi Bereznyi, 70 km from the regional centre – Uzhhorod and 7 km from the Kostryno railway station on the Chop–Sambir line. The Vyshka River, a left tributary of the Uzh, originates in the village.
5. Mount Yavirnyk (coordinates where measurements were made: 48°54′56.7″N 22°32′27.6″E, maximum value of night sky brightness – 21.50 mag·arcsec^{-2}, measurement dates: June 17, 2021) – is a 1017-metre peak of the Ukrainian Carpathians, which is located within the Polonyn Beskids. It is located in the Uzhhorod district of the Zakarpattia region, in the eastern direction from the Velykyi Bereznyi village.

Analysis of light pollution of the night sky in the city of Uzhgorod and in the village of Nizhny Solotvino (Derenivka) from 1983–2021

In March 2005, at the Uzhhorod Astronomical Observation Point (Uzhhorod Observatory on Mount Calvary), measurements of the brightness of the night sky were made at the zenith using a photometer that covered an area of the sky with s field of view of about 9°. Observations were performed with a yellow-green filter, the effective transmission wavelength of which was 556 nm. The bandwidth of the filter was 80 nm. The brightness measurement error was 0.08 mag·arcsec^{-2}. Research was conducted on clear, moonless nights. Cloudiness did not exceed two points on a 10-point scale. Snow cover was absent, as well as the solar component in illumination because during all observations, the height of the sun above the horizon reached more than minus 18° (Yepishev et al. 2005).

The average value of the brightness of the night sky was 20.2 mag·arcsec^{-2}, and the average square deviation of the brightness values from the average value was σ = 0.60 mag·arcsec^{-2}. The obtained data was compared with the results of similar observations of the brightness of the night sky in Uzhgorod, which were performed in 1983 on the same device, when the average value of the brightness of the night sky was 20.7 mag·arcsec^{-2}.

The increase in the brightness of the night sky (Δm at the zenith) over twenty-two years above Calvary, is approximately equal to 0.5 mag·arcsec^{-2} or 1.6 times. Large cities at a great distance cause almost the entire sky to glow. Due to the bad astroclimate, a new observation point was created in Nizhny Solotvino village (Derenivka observation point) at a distance of 15 km from Uzhgorod city, where the brightness of the night sky at the zenith is 21.5 mag·arcsec^{-2} and is almost 3.5 to 5.0 times better than in the Calvary region. However, in recent years, the astroclimate has also worsened there due to the creation of resort complexes, the lighting of highways, etc.

In June–October 2021, we also measured the brightness of the night sky at the Uzhgorod astronomical observation point (Laboratory of space research UzhNU on Mount Calvary) with the SQM device. The average value was 19.72 mag·arcsec^{-2}. At the same time, the brightness of the night sky brightness was also measured at the Derenivka observation point with SQM device; the average value there was 21.18 mag·arcsec^{-2}. As we can see from the measurement results, the closer to the city, the brighter the sky.

The maximum values of the passband effective transmission are almost the same as those reported in the paper by Bará et al. (2019), 556 nm with the photometer used in 1983-2005 and ~510 nm with the SQM device. This enables the carefully comparison of the obtained data.

Conclusions

From June to November 2021, the night sky brightness was measured on the territory of the Transcarpathian Dark-Sky Park. We performed all measurements at night, when the moon was in the new moon or crescent moon phases. We conducted measurements along the perimeter of the Transcarpathian Dark-Sky Park, namely on Mount Yavirnyk (near the village of Velikiy Berezny) as well as near the settlements of Lubnya village, Knyahynya village, Uzhok village and Vishka village. For comparison, we also conducted measurements in the city of Uzhhorod and in the village of Nizhne Solotvino (Derenivka observation point) because we had archival results of measurements from 1983 and 2005.

In all locations of the Transcarpathian Dark-Sky Park where we performed measurements, the average value of the night sky brightness was equal to or greater than 21.50 mag·arcsec^{-2}.

Continuous monitoring of the brightness of the night sky allows recording the specific light pollution in each location, taking into account the difference in weather conditions, climate and different phases of the moon, as well as the ability to study long-term trends.

The modal value of the brightness of the night sky varied from 19.73 to 21.92 mag·arcsec^{-2}, which confirms the great variability of light pollution depending on the position of the site, in particular, the height of the site and its distance from the main sources of pollution, as well as various climatic changes, which play an important role.

Tab. 7.1. Average measurements on night sky brightness in Transcarpathian Dark-Sky Park and surrounding areas

№	Measurement locations	Date yyyy-mm-dd	Max value mag·arcsec^{-2}	Coordinates latitude, longitude, height (meters)		
1	Uzhhorod	2021-06-17	19.73	48°38′01.8″N	22°17′55.4″E	182
2	Uzhhorod	2021-10-16	19.75	48°38′01.8″N	22°17′55.4″E	182
3	Uzhok	2021-09-08	21.67	49°00′07.4″N	22°53′14.96″E	889
4	Uzhok	2021-09-09	21.66	49°00′07.4″N	22°53′14.96″E	889
5	Lubnya	2021-08-09	21.80	49°02′09.2″N	22°43′05.9″E	583
6	Lubnya	2021-08-10	21.71	49°02′09.2″N	22°43′05.9″E	583
7	Lubnya	2021-08-11	21.80	49°02′09.2″N	22°43′05.9″E	583
8	Lubnya	2021-08-12	21.70	49°02′09.2″N	22°43′05.9″E	583
9	Lubnya	2021-08-13	21.92	49°02′09.2″N	22°43′05.9″E	583
10	Lubnya	2021-08-14	21.71	49°02′09.2″N	22°43′05.9″E	583
11	Vishka	2021-10-08	21.46	48°56′34.0″N	22°39′57.0″E	635

12	Vishka	2021-10-09	21.49	48°56′34.0″N	22°39′57.0″E	635
13	Vishka	2021-10-10	21.47	48°56′34.0″N	22°39′57.0″E	635
14	Knyahynya	2021-08-09	21.60	48°58′28.9″N	22°30′47.5″E	512
15	Knyahynya	2021-08-10	21.55	48°58′28.9″N	22°30′47.5″E	512
16	Knyahynya	2021-08-11	21.62	48°58′28.9″N	22°30′47.5″E	512
17	Knyahynya	2021-08-12	21.53	48°58′28.9″N	22°30′47.5″E	512
18	Knyahynya	2021-08-13	21.55	48°58′28.9″N	22°30′47.5″E	512
19	Knyahynya	2021-08-14	21.54	48°58′28.9″N	22°30′47.5″E	512
20	Derenivka	2021-07-13	20.80	48°33′48.4″N	22°27′13.1″E	238
21	Derenivka	2021-07-17	20.87	48°33′48.4″N	22°27′13.1″E	238
22	Derenivka	2021-08-04	21.18	48°33′48.4″N	22°27′13.1″E	238
23	Yavirnyk	2021-06-17	21.50	48°54′56.7″N	22°32′27.6″E	985

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ZANIECZYSZCZENIE ŚWIETLNE I JEGO WPŁYW NA ŚRODOWISKO NATURALNE

S t r e s z c z e n i e

Monografia prezentuje zagadnienie wpływu zanieczyszczenia świetlnego na środowisko naturalne oraz zdrowie człowieka. Wskazano na możliwość zakłócenia równowagi między nietoperzami a przenoszonymi przez nie RNA wirusami, które w warunkach stresu wywołanego obecnością ALAN mogą być rozsiewane w środowisku i przyczyniać się do rozwoju pandemii COVID-19. Poruszony został problem coraz silniejszego oddziaływania oświetlenia nocnego na postrzeganie świata przez człowieka. Przeanalizowano różnego rodzaju oświetlenie miast, zarówno użytkowe, jak i ozdobne, pod kątem jego potencjalnej szkodliwości dla nocnego środowiska naturalnego. Zaprezentowano zarówno krajowe, jak i światowe przykłady regulacji prawnych związanych z tego rodzaju oświetleniem oraz sposobów przeciwdziałania jego negatywnym aspektom. W związku z zamierzoną budową pierwszej elektrowni jądrowej w Polsce przedstawiono aktualny stan poziomu zanieczyszczenia świetlnego na terenie planowanej budowy. W przyszłości, po zakończeniu budowy, pozwoli to na ocenę wpływu tego rodzaju inwestycji na nocne środowisko naturalne. Zaprezentowano również sieć monitoringu zanieczyszczenia świetlnego działającą na obszarze dużego miasta, a także analogiczną sieć działającą na obszarze wolnym od zanieczyszczenia świetlnego.

Słowa kluczowe: zanieczyszczenie świetlne, ekosystemy nocne, COVID-19

LIGHT POLLUTION AND ITS IMPACT ON THE NATURAL ENVIRONMENT

Summary

The monograph presents the issue of the impact of light pollution on the natural environment and human health. In particular, it is highlighted that night lighting could have an impact on shedding of zoonotic RNA viruses normally present in the bats' organisms, but under the stress conditions could heave led to the development of the COVID-19 pandemic. The problem of the increasingly strong impact of night lighting on the human perception of the world was raised. Various types of city lighting, both functional and decorative, are analysed in terms of their potential harmfulness to the natural environment at night. Both domestic and global examples of legal regulations related to this type of lighting and methods of counteracting its negative aspects are presented. In connection with the intended construction of the first nuclear power plant in Poland, the current state of the light pollution level in the planned construction site is presented. In the future, after construction is completed, this will enable the assessment of the impact of this type of investment on the natural environment at night. A light pollution monitoring network operating in a large city is also presented, as is a similar network operating in an area free from light pollution.

Keywords: light pollution, night ecosystems, COVID-19

LICHTVERSCHMUTZUNG UND IHRE AUSWIRKUNGEN AUF DIE NATÜRLICHE UMWELT

Zusammenfassung

Die Monographie befasst sich mit den Auswirkungen der Lichtverschmutzung auf die natürliche Umwelt und die menschliche Gesundheit. Es wurde auf die Möglichkeit einer Störung des Gleichgewichts zwischen Fledermäusen und den von ihnen übertragenen RNA-Viren hingewiesen, die sich unter Stressbedingungen, die durch das Vorhandensein von ALAN verursacht werden, in der Umwelt verbreiten und zur Entwicklung der COVID-19-Pandemie beitragen können. Es wurde das Problem des immer stärkeren Einflusses der Nachtbeleuchtung auf die menschliche Wahrnehmung der Welt angesprochen. Verschiedene Arten der Stadtbeleuchtung, sowohl funktionale als auch dekorative, wurden im Hinblick auf ihre potenzielle Schädlichkeit für die natürliche Umwelt bei Nacht analysiert. Es wurden sowohl nationale als auch globale Beispiele für gesetzliche Regelungen im Zusammenhang mit dieser Art von Beleuchtung und Methoden zur Bekämpfung ihrer negativen Aspekte vorgestellt. Im Zusammenhang mit dem geplanten Bau des ersten Kernkraftwerks in Polen wurde der aktuelle Stand der Lichtverschmutzung auf der geplanten Baustelle vorgestellt. Dies wird künftig nach Abschluss der Bauarbeiten eine Beurteilung der Auswirkungen dieser Art von Investition auf die natürliche Umwelt in der Nacht ermöglichen. Außerdem wurde ein Netzwerk zur Überwachung der Lichtverschmutzung vorgestellt, das in einer Großstadt betrieben wird, sowie ein ähnliches Netzwerk, das in einem Gebiet ohne Lichtverschmutzung betrieben wird.

Schlüsselwörter: Lichtverschmutzung, Nachtökosysteme, COVID-19