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Lighting of pedestrian and pedestrian-driving routes in a housing estate as a source of light pollution

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Abstract

This paper is devoted to the extremely important issue of lighting pedestrian and pedestrian-driving routes within a housing estate. Both aspects are discussed with regard to the safety of route users and the potential impact on the natural environment through the phenomenon of light pollution. It was found that most of the outdated high-pressure sodium lamps present in the analysed Podwawelskie housing estate in Kraków do not fulfil their basic purpose, which is to sufficiently illuminate the ground below. Nevertheless, the light of these lamps does not make a noticeable contribution to the basic form of light pollution, which is the city's sky glow. It has been suggested that it would be best to replace these types of lamps with LED lighting, which has already been partly done. The LED lamps provide lighting that is sufficient to ensure the safety of residents. However, their improper installation may cause glare for pedestrians or residents of neighbouring houses. Additionally, their light reflected from an excessively bright pavement makes a significant contribution to the artificial sky glow. Solutions are proposed that minimise the negative impact of this lighting on the environment while ensuring comfort for the residents of the estate, which is in line with the principles of sustainable development.

Keywords: lighting, lamps, light pollution, safety

1. Introduction

The area of modern cities can be divided into several parts. These most frequently include:

- the historical centre,
- the surrounding multi-family housing estates,
- office complexes,
- industrial areas,
- peripheral estates of single-family houses.

Each of the above-mentioned parts contribute to the light pollution of the night sky (artificial sky glow) generated by the city (Walker, 1977; Brons et al., 2008; Ścieżor, 2012; Guanglei et al., 2019; Ścieżor, 2019b; Helbich et al., 2020; Zielińska-Dąbkowska et al., 2020; Pothukuchi, 2021). While the lighting of the historic centre (Fila et al., 2014; Kobav et al., 2021) and office complexes has already been analysed (Parkins et al., 2015; Du et al., 2018; Kobav et al., 2021; Ścieżor, & Czaplicka, 2022), the impact of the remaining components has not yet been properly investigated. The issue of lighting in housing estates seems to be of particular interest as they occupy a significant part of the city's area – in Kraków, this amounts to around 10% of the area within the administrative borders. These estates, usually peripheral to the city centre, most often serve as "bedrooms" for residents who spend mainly evenings and nights there. Therefore, the issue of lighting pedestrian and pedestrian-driving routes in these areas is of importance as it determines the safety of housing estates for residents both returning from their job in the afternoon or early evening hours and shopping at that time (Kretzer, 2020). This problem is exacerbated in the autumn and winter period when early darkness necessitates the use of artificial lighting.

Even the lighting of pedestrian and pedestrian-driving routes of housing estates that are currently being built often does not only fail to meet the safety requirements of users but also makes a significant contribution to light pollution in the form of artificial sky glow. This issue is even more serious in the case of the older housing estates, where the lighting, often installed at the time of the construction of the estate and remaining until today, is inappropriately complemented with more modern solutions, sometimes while also not fully serving their purpose. An example of such a housing estate is the Podwawelskie estate in Kraków.

2. Research area

The research subject was the Podwawelskie housing estate in Kraków, part of District VIII "Dębniki". The estate is located on the western side of the Vistula river, near the historic centre of Kraków. Its shape resembles a rectangle bordered by Konopnicka street from the east, Dworska and Wierzbowa streets from the north, Kapelanka street from the west and the Wilga valley from the south (Fig. 1).

The complex of the Podwawelskie housing estate was created as a result of an architectural competition completed in 1965. The "estate-park" project was prepared by the team of prof. Witold Cęckiewicz. The urban layout of the estate consists of long, four-story apartment buildings with their elevations facing south, arranged in parallel stripes in four rows (5.16 Podwawelskie, 2022; Cęckiewicz, 2015: 172-173). Such an arrangement of buildings, from west to east, enables the proper ventilation of the complex in accordance with the direction of most winds in Kraków. The estate also includes sixteen ten-story high-rise buildings. These were located in grassy spaces (Cęckiewicz, 2015: 172-173), on the western, southern and eastern outskirts of the Podwawelskie estate area. Several commercial and service pavilions complete the complex. Through the centre of the estate, along its north-south axis, there is a green walking route which is its main open green area, closed from the south by the Church of Our Lady of Fatima. The development of the urban complex of the Podwawelskie estate took

Fig. 1. The area of Kraków with the Dębniki district (marked grey) and the Podwawelskie estate (marked red). (own elaboration)

place in the years 1967-1976 (5.16 Podwawelskie, 2022). The Podwawelskie estate has received many awards for the best-designed housing estate in Poland – it is green, with adequate air circulation and good infrastructure. Compared to other, newer housing estates in Kraków, a significant percentage is taken up by greenery – inter-block spaces, playgrounds, sports grounds, and walking paths. The area of the Podwawelskie estate is approx. 421,000 m^2 (which is 0.1% of the area of the entire city), of which greenery takes up approx. 185,000 m^2, i.e. as much as 44% of the analysed space.

Three types of routes can be distinguished inside the Podwawelskie estate: streets, intended for vehicular traffic only; pedestrian routes, intended for pedestrian traffic only; pedestrian-driving routes, which are intended primarily for pedestrian traffic, however, vehicles may be driven on them to a limited extent (e.g. access to parking spaces). The total length of all these routes is almost 40,000 m, of which the streets are approx. 4,000 m (10%), and illuminated pedestrian and pedestrian-driving routes make up the remaining 36,000 m (90%). There is no industry developed on the estate – almost all of its area is occupied by multi-family housing, and there are only a few small commercial and service pavilions. In the southern part of the Podwawelskie estate, there is an unlit nursery of trees and shrubs "Ogrody Ludwinów", while the south-eastern part is also an unlit grassy meadow, used as an exercise area for dogs.

The following types of light sources have been identified in the Podwawelskie estate area:

- street lamps,
- lamps illuminating pedestrian and pedestrian-driving routes,
- lamps illuminating parking areas,
- advertising lights,
- apartment/internal lighting.

The first of these types (street lamps) has already been analysed (Ścieżor, 2021). The subject of this analysis is the lighting of pedestrian and pedestrian-driving routes in the area of the Podwawelskie estate. Other types of lighting are under research.

3. Types of lamps used in outdoor lighting

Currently, the following light sources are used in lamps that illuminate streets, pedestrian routes and pedestrian-driving routes (Exterior lighting guide for federal agencies, 2010; Żagan, 2014; Gutierrez-Escolar et al., 2015; The Lighting Handbook, 2018), which to a different extent, affects the level of light pollution (Luginbuhl et al., 2014):

- Sodium lamps. These are gas discharge lamps in which the discharge environment is sodium vapour. With reference to the pressure of sodium vapour in the arc tube, they are divided into low-pressure (LPS) and high-pressure (HPS) sodium lamps:

- LPS lamps generate, as a result of the discharge in a sodium vapour environment at a pressure less than 1 Pa, almost monochromatic light concentrated around a double sodium emission line with wavelengths of 589.0 and 589.56 nm. Currently, lamps with power from 18 to 180 W are produced. They achieve luminous efficacy of up to 206 lm/W, the highest among used artificial light sources. Unfortunately, the yellow-orange light emitted by them with a Correlated Colour Temperature (CCT) of 1,800 K, with very poor colour rendering properties limited their use for almost exclusively lighting highways, express roads and tunnels with no pedestrian traffic. Their durability is up to 16,000 hours. Currently, they are almost never used.
- HPS lamps produce, as a result of the discharge in the environment of sodium vapour at a pressure of approx. 2 Pa, light with a CCT of 2,200 K, perceived as yellow-golden or orange. Their luminous efficacy is 68–150 lm/W. They are built with a rated power of 50 to 1,000 W, and their durability, depending on their design, ranges from 10,000 to 24,000 hours. As a result of their better colour rendering, they have a wider application than LPS lamps. In the light of sodium lamps, the sharpness of vision in dust and fog increases, thus they are a very good source for illuminating communication arteries, factory yards and open areas. Since the spectrum of sodium lamps is in the range of photosynthetically active radiation, they are used in plant cultivation.

- Mercury vapour lamps (MV). These are discharge lamps in which the discharge environment of the electric arc is mercury vapour at a pressure of 0.2 to 1 kPa. They produce bluish-white light with a high proportion of ultraviolet light. In the case of a phosphor-coated housing, the ultraviolet energy emitted from the arc tube is converted into radiation energy in the red range. Their luminous efficacy exceeds 40–50 lm/W, which makes them worse in this respect than sodium and metal halide lamps, as well as modern linear fluorescent lamps, therefore they are not used in new installations. Previously, they were widely used in outdoor lighting, industrial halls and warehouses. Mercury vapour lamps are produced with the power of 50 W to 2,000 W.
- Metal halide lamps (MH). These are discharge lamps in which light is generated by an electric discharge in a mixture of mercury, argon and metal halides (sometimes also other noble gases and bromine or iodine) under high pressure, so such lamps are high-pressure. These lamps are characterised by their high luminous efficiency (80–125 lm/W), long service life (from 7,500 to 20,000 hours) and very good colour rendering of the surroundings, and the CCT can be from 3,000 K to over 7,000 K, depending on the mixture used; therefore, they are applied both in indoor and outdoor lighting, especially for the illumination of architectural objects, including the historic districts of cities around the world.
- Light-emitting diode lamps (LED). In these lamps, the light source is a light-emitting diode and a phosphor. The phosphor emits yellow-green light which, when mixed with the blue light of the diode, gives white light. Depending on the type of phosphor, white can be obtained with a different CCT. The main advantages of LED lamps include their high durability, exceeding 15,000 hours, high efficiency, their ability to obtain any colour of light without the use of coloured filters, their low operating price and the absence of ultraviolet (UV) radiation that is harmful to human eyes and skin as well as being damaging to works of art. The luminous efficiency of LED lamps is 70-180 lm/W (it can be up to 300 lm/W). Another advantage is their high colour rendering index of the

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surroundings. The disadvantage of this type of lighting is the widespread use of lamps with a high CCT, adversely affecting humans and other living creatures (Tähkämö et al., 2019).

In the area of the Podwawelskie estate, the following types of lamps illuminating the pedestrian and pedestrian-driving routes have been identified (Fig. 2):

B_{HPS} – free-standing lamps with a spherical cover, without a holder (HPS type) (height: 4.5 m);
E_{LED-S} – facade lamps with a flat luminaire, mounted on the side facades of buildings, located along the pedestrian routes (LED type) (height: 6.5 m);
E_{LED-E} – facade lamps with a flat luminaire, mounted above the entrances to buildings, located along the pedestrian and pedestrian-driving routes (LED type) (height: 5.5 m);
F_{LED} – free-standing lamps with a flat luminaire (LED type) (height: 4.5 m);
H_{MV} – free-standing lamps with a top-down hat-like casing, additionally shielded from the neighbouring buildings (MV type) (height: 4.5 m);
H_{HPS} – free-standing lamps with a top-down hat-like casing, additionally shielded from the neighbouring buildings (HPS type) (height: 4.5 m);
R_{LED} – free-standing lamps with a top-down brim-like casing (LED type) (height: 5.5 m). According to the manufacturer's description, the aperture in the central part of the lampshade and the canopy (brim) shape the light beam and effectively reduce light emission upwards.

Fig. 2. Types of luminaires illuminating the pedestrian and pedestrian-driving routes in the Podwawelskie estate in Kraków (own elaboration)

The B_{HPS} lamps (133 units) dominate the pedestrian routes that cross the green areas inside the estate as well as lawns between these routes. These lamps, installed back in the 1970s, along with the construction of the housing estate, are characterised by a high degree of degradation of both their spherical covers (in particular their upper parts, exposed to weather conditions and biological damage), as well as the light sources themselves (HPS). Regardless of the measurements carried out, the visual assessment of these lamps is negative – they do not sufficiently illuminate the targeted areas, giving the impression of darkness. Moreover, they were placed in areas treated as the housing estate's parks, and as a result, they often stand between trees, in the middle of the lawn, or even with their covers hidden in the treetops.

At the intersections of some pedestrian routes, as well as at kindergartens and some playgrounds, B_{HPS} lamps were later replaced with R_{LED} lamps (13 units), significantly improving the lighting of the surrounding area. H_{MV} and H_{HPS} lamps

(1 and 2 units, respectively) were placed next to one building complex in 2015. Due to the impossibility of approaching these lamps (fenced area), measurements were made for lamps of similar design located in the neighbouring housing estate, right next to the western border of the Podwawelskie estate.

In the vicinity of another group of buildings, built in 2000–2002, B_{HPS} lamps were replaced with F_{LED} lamps (4 units, mounted on the same masts as the older ones) in 2021, which made it possible to compare the illumination produced by these two types of lamps.

Some of the pedestrian routes, leading along the facade of apartment buildings, which were originally not lit (or illuminated with "park" lamps of B_{HPS} type), were illuminated a few years ago by installing E_{LED-S} and E_{LED-E} lamps on them (89 units, usually 2-3 on each building). E_{LED-E} lamps are mounted above the canopies protecting the entrances to the buildings. The entrances themselves are illuminated by LED panels in a cover informing about the block number. Unfortunately, some of these panels do not work, so the immediate vicinity of the front door is plunged into deep shadow, intensified by the contrast with the neighbouring area, which is brightly lit by E_{LED-E} lamps.

4. Used units

4.1. Radiometric units

The radiance value is obtained from the VIIRS/DNB satellite data, i.e. the radiation flux per unit area per unit solid angle. The symbol for radiance is L, while the standard SI unit is W/m²·sr (Teikari, 2007). In this publication, radiance values are given in the derived units nW/cm²·sr, in which VIIRS/DNB data are provided.

4.2. Photometric units

The measure of the visual impression received by the eye from the glowing surface is luminance. In the SI system, it is expressed in the unit of candela per square metre (cd/m²).

The Unihedron SQM meters, used for measuring the surface brightness of the sky, report the value of the surface brightness of the night sky (denoted as S_a) in astronomical units of magnitude per squared arc-second (mag/arcsec²). This scale determines the surface brightness of blurry astronomical objects, such as nebulae, galaxies, comets, or the sky background. The TSL237 frequency sensor used in the meters has a frequency output proportional to the measured brightness with a response of 2.3 kHz (µW/ m²). However, the meter manufacturer does not provide the algorithm used to convert the sensor scale (µW/cm²) to the meter scale (mag/arcsec²). Only the relationship between the surface brightness and the luminance scale is given. This relationship is not obvious, but assuming a linear correlation between the surface SQM brightness (luminance) perceived by the eye and the physical surface brightness, one can identify the relationship (Crawford, 1997; Bará et al., 2019; Kyba et al., 2011):

$$(\mathrm{mag/arcsec^2}) = 12.59 - 2.5\log[(\mathrm{cd/m^2})], \tag{1}$$

that is,

$$[\mathrm{cd/m^2}] = 10.8 \times 10^4 \times 10^{[-0.4(\mathrm{mag/arcsec\^{}2})]} \tag{2}$$

Due to the very low surface brightness of the night sky, a commonly used unit is millicandela per square metre (mcd/m²).

In this publication, SQM measurement results are given in both mag/arcsec² and the corresponding mcd/m².

The illuminance (E) is given in lux (lx).

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5. Methodology of measurements

5.1. Remote sensing

To determine the total radiance from the studied area, images obtained from the Suomi National Polar-orbiting Partnership (SNPP) satellite were used. This satellite was launched in 2011 by the US National Oceanic and Meteorological Service (NOAA) (Wolfe et al., 2013). A VIIRS (Visible Infrared Imaging Radiometer Suite) camera was installed on board the satellite, equipped with the best sensors and optical systems that have been used so far in civilian missions. For this study, photos taken in the spectral range of DNB (Day-Night Band) with a spatial resolution of 750 m (Elvidge et al., 2013) are useful. To avoid disturbing effects (moonlight, clouds), only VIIRS/DNB cloud-free composites taken during cloudless and moonless nights were used for the analysis (LAADS DAAC, 2022). Instead of having 750-metre standard resolution, cloud-free composite data are binned into a 15-arcsecond grid spanning from 65 south to 75 north latitude (Kyba et al., 2015). The pixel size therefore depends on the latitude. It was found that in the VIIRS cloud-free composites covering the Podwawelskie estate area, the dimensions of a single pixel are around 465 × 300 m so that its image covers 4 pixels, which is 93% of the area of the estate. The northern parts of the two pixels also include some of the buildings of the neighbouring estate (Dębniki, with an area of 8% of the examined Podwawelskie estate), but the nature of these buildings and lighting is similar to the Podwawelskie estate. As a result, it should be stated that the source of the radiance determined in this way can be entirely associated with the lighting of the Podwawelskie estate. The comparison of the described VIIRS/DNB images with the night photo of Kraków taken from the ISS in 2017 (Zamorano et al., 2011; Sánchez de Miguel et al., 2019; GAPE, 2021), in which the size of a single pixel is 13.5 × 13.5 m, enables the identification of the main light sources in the Podwawelskie estate.

Due to the analysis of the period of the switching off municipal lighting in April and May 2020, related to the COVID-19 pandemic (Ścieżor, 2021), it should be noted that VIIRS/DNB photos of the studied area were taken during this period at around 0:10 UTC, i.e. 2:10 CEST. The clocks that turned off the street lighting at midnight in this period were operated in Poland according to CEST, so the VIIRS/DNB photos were taken when the lighting had been already turned off.

The radiance value is obtained from the VIIRS/DNB satellite data, i.e. the radiation flux per unit area per unit solid angle. The symbol for radiance is L, while the standard SI unit is $W/m^2 \cdot sr$ (Teikari, 2007). In this paper, radiance values are given in the derived units $nW/cm^2 \cdot sr$, in which VIIRS/DNB data are provided.

5.2. Measurements of the brightness of the sky glow

Measurements of the surface brightness of the night sky (sky glow) were performed using the Unihedron Sky Quality Meters (SQM). These meters are produced in several versions, of which only the manually triggered SQM-L with the light-gathering angle of 20° from the instrument axis was used in the described tests (Cinzano, 2007). During the measurements, they were directed towards the zenith with an accuracy of approx. 3°. The accuracy of the measurement, provided by the manufacturer, is 0.1 $mag/arcsec^2$; however, multiple measurements have shown that the amplitude of changes in the S_a value in each tested meter under stable atmospheric conditions does not exceed 0.02 $mag/arcsec^2$. Therefore, the measurement was triggered until three consecutive readings were consistent with 0.02 $mag/arcsec^2$ and no trend was observed during this time. However, the S_a values in this paper are rounded to 0.1 $mag/arcsec^2$.

Measurements of the surface brightness of the night sky were made at two measurement points in the area of the Podwawelskie estate: Point A was located in the western part of the estate, in an area strongly illuminated by street lighting (Słomiana street), by park-type lamps illuminating pedestrian and pedestrian-driving routes and by lamps illuminating local parking spaces. Point B was located at the southern edge of the estate, in the area of plots where the only source of light is street lighting on Rozdroże street. During the lockdown period (April-May 2020), initially (in April) only municipal street lighting and parking lighting were turned off (including the internal streets of the Podwawelskie estate), then (in May) street lighting was turned off first, and then (after approx. three minutes) lighting of pedestrian and pedestrian-driving routes in the estate.

Measurements were made both under the cloudless and overcast sky, but only during moonless nights. This allowed determining the impact of the analysed lighting on the level of light pollution in the category of artificial sky glow.

5.3. Illuminance measurements

A Sonopan P-200 control panel equipped with a highly sensitive L-200 photometric head with a measurement resolution of 0.001 lx was used to measure the illuminance. Measurements were taken at ground level, with the measuring window of the luxmeter facing the zenith. The illuminance was measured on the ground, near the individual types of lamps, starting from their base, at 1 m intervals, up to a distance of several meters. Example lamps of a given type were chosen in such a way that the measured illuminance was minimally influenced by other, neighbouring light sources.

In addition, knowing about the planned replacement of some lamps from B_{HPS} to F_{LED}, measurements of the illuminance were also carried out in the plane of the windows on the each floor of the eleven-story apartment building before and after the replacement. These measurements made it possible to determine the contribution of these types of pedestrian street lighting to light pollution in the *trespass* category. In addition, in both cases, the illuminance of the surface of the pedestrian-driving route illuminated by these lamps was also measured, both in the transect parallel to the building facade and in perpendicular transects.

To minimise the background illumination effect of city lights reflected from clouds, measurements were taken under a cloudless sky.

5.4. Spectral analysis

Identification of the types of light sources in lamps was made using AstroMedia diffraction grids (Artikel Nr.407.NDI) with a constant grating equal to 1000 lines/mm and a proprietary spectroscope based on a double dispersion à vision directe prism (Amici prism) (Hagen, & Tkaczyk, 2011; Zamorano, 2020).

5.5. Equidensitometry

Based on photographs taken with a Canon 800D camera (RAW CR2 format) of the surroundings of the described types of lamps, a photometric analysis (equidensitometry) of the areas illuminated by them was performed consisting of replacing the photographic image with an image made of lines running through points of the same optical density (equidensities) (Brown, 2010). The brightness range of pixels in the Canon images was divided into five equal intervals, each of which was assigned the appropriate colour on a scale from blue (lowest brightness – 0 arb. unit) to red (highest brightness – 255 arb. unit).

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6. Results

6.1. Remote sensing

Based on the analysis of the calibrated ISS image, it can be concluded that the visible areas of brightness are, in each case, related either to the streets or to illuminated ground parking areas (Fig. 3). The conducted field survey shows that it is not the direct light, emitted by the lamps illuminating these objects, but reflected light from the bright surface of streets and parking lots. There are no visible areas of brightness related to the pedestrian or pedestrian-driving routes in the area of the Podwawelskie estate.

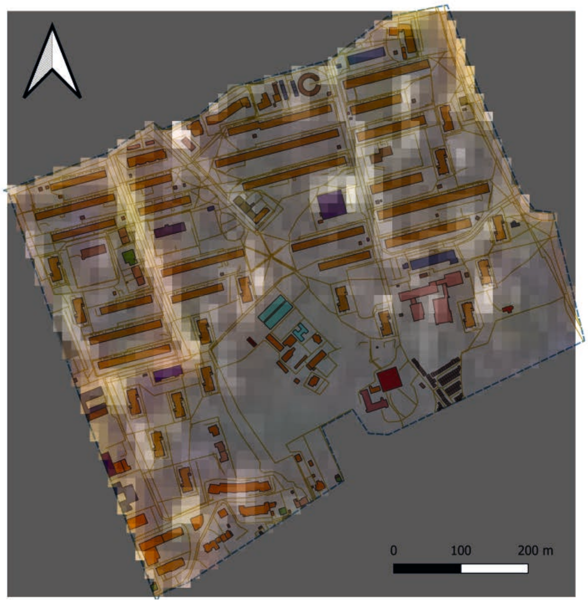

Fig. 3. Schematic GIS map of the Podwawelskie estate in Kraków overlaid on a ISS image of this area (GAPE, 2021). Bright areas related to streets and parking lots are visible (own elaboration)

The shutdown of municipal lighting in Kraków in the period from April 15th to the end of May 2020 made it possible to quantify the effect of individual types of lighting on radiance.

On a cloudless and moonless night preceding the period of lockdown (13/14.04), a radiance from the Podwawelskie estate area of 172 nW/cm^2·sr was measured. From the night of April 15th/16th, all street lighting and parking lights were turned off at midnight, but the pedestrian and pedestrian-driving routes on the Podwawelskie estate remained illuminated. During this period, a significant decrease in radiance was found in similar conditions as before (as well as the same satellite angle), on the night of April 21st/22nd, it was equal to 81 nW/cm^2·sr. In May, the lighting of pedestrian and pedestrian-driving routes was also turned off. The total radiance measured in this period from the Podwawelskie estate

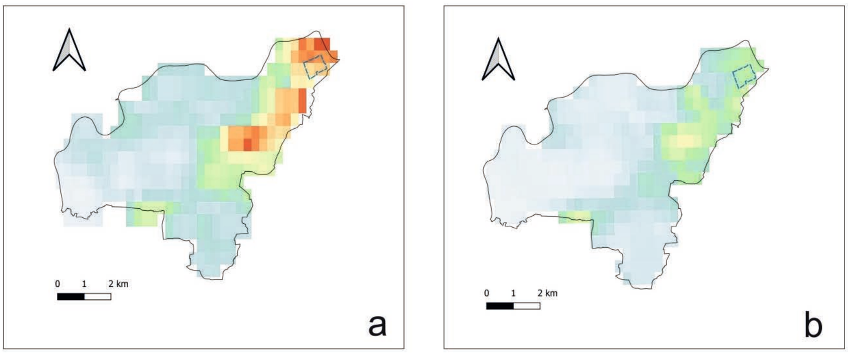

Fig. 4. Map of radiance from the area of Dębniki district in Kraków in March (a) and May 2020 (b). The area of Podwawelskie estate is marked with a dotted line in the north-eastern part of the district. The colours correspond to radiance from 0 (white) to 70 nW/cm2·sr (red) (own elaboration based on data from (LAADS DAAC, 2022))

area was 72 nW/cm²·sr (night of May 14th/15th). After restoring the full lighting in the Podwawelskie estate, the measured radiance was 180 nW/cm²·sr (night of August 21st/22nd). Similar values were measured for other cloudless and moonless nights in the analysed period.

6.2. Measurements of the brightness of the sky glow

The first systematic measurements of the surface brightness of the night sky (sky glow) in the Podwawelskie estate area were carried out in 2008–2010 (Ściężor et al., 2010). The mean value of S_a measured then for a cloudless and moonless sky was 18.0 mag/arcsec², while for an overcast sky, it was 15.7 mag/arcsec², which corresponds to the luminance of 6.9 mcd/m² and 57.2 mcd/m², respectively.

With regard to the analysis of the impact of the Podwawelskie estate lighting on the brightness of the artificial sky glow, the power failure in the areas of the Dębniki and Podwawelskie estates, which occurred on the evening of August 25th, 2011, was extremely interesting (Ściężor, 2019a). As a result, these estates were deprived of any lighting for several hours. During the failure, with the sky slightly overcast with high clouds (*Cirrus* type), S_a = 18.1 mag/arcsec² (6.44 mcd/m²) was measured. While the failure was being repaired, only a part of the Podwawelskie estate was deprived of lighting for some time – then the measured value of S_a = 17.7 mag/arcsec² (8.90 mcd/m²). After the failure was repaired, S_a = 17.5 mag/arcsec² (10.9 mcd/m²) was measured.

Another series of measurements in the Podwawelskie estate area was related to the COVID-19 pandemic lockdown in 2020. It was found that with a cloudless and moonless sky, the S_a value increased from 18.6 mag/arcsec² with the lighting fully on, to 19.1 mag/arcsec² with street and parking lights off, and then to 19.2 mag/arcsec² with all lighting turned off, including the lighting of pedestrian and pedestrian-driving routes. This means a reduction in luminance from the initial 4.1 mcd/m² to 2.5 mcd/m² and then to 2.2 mcd/m². In the case of a completely overcast sky with low *stratus* clouds, the corresponding values of S_a (and of the luminance) were equal to 15.5 mag/arcsec² (68.7 mcd/m²), 16.2 mag/arcsec² (36.1 mcd/m²) and again 16.2 mag/arcsec² (36.1 mcd/m²).

6.3. Measurements of the illuminance

For the area not illuminated by lamps in the Podwawelskie estate area, the "natural" illuminance was measured. In the case of a cloudless sky, the result was 0.18 lx and for an overcast sky, it was 0.5–3.2 lx (depending on the type of clouds). These values should be treated as the natural urban background of the analysed area.

Figure 5 presents the results of measurements of the luminance vs. the distance from individual types of lamps at the ground level in the direction of the main illumination. The measured maximum values of illuminance for individual types of lamps vary from approx. 75 lx (F_{LED} lamps) to only approx. 3 lx (B_{HPS} lamps). In a few cases (E_{LED-S}, E_{LED-E}, B_{HPS}) the area directly under the lamp is too dimly lit, which is related either to the design of the luminaire and the installation of the lamp itself (E_{LED-S}, B_{HPS}) or to its installation in an incorrect place (E_{LED-E}). In particular, the difference between E_{LED-S} and E_{LED-E} lamps is visible. In the first case, regardless of the illumination by the lamps themselves, the ground is also illuminated by their light reflected from the lower parts of the white walls of the buildings. In the case of E_{LED-E} lamps, the effect is quite the opposite. Their installation above the canopies covering the entrances to buildings means that its light is reflected only from a small part of the wall between the lamp and the canopy. Furthermore, the part of the area in front of the entrance is located in the shadow cast by the canopy, which requires additional lighting for the entrances themselves.

In the case of H_{MV} and H_{HPS} lamps, due to the inaccessibility of the lamps (restricted area), measurements were made for lamps of the same type and structure located in the neighbouring housing estate, near the western border of the Podwawelskie estate.

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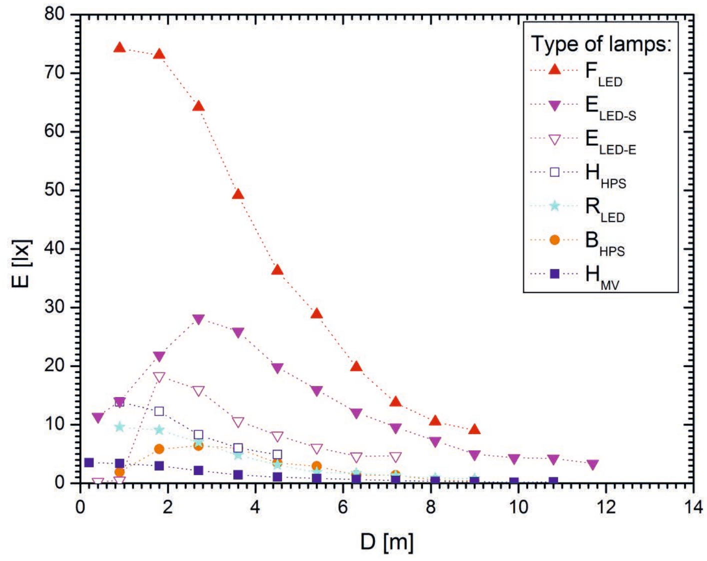

Fig. 5. Illuminance vs. distances from individual types of lamps in the Podwawelskie housing estate in Kraków (own elaboration)

With regard to the replacement of lamps illuminating the pedestrian and pedestrian-driving routes in front of one of the blocks in the Podwawelskie estate (B_{HPS} lamps were replaced with F_{LED} lamps), measurements of the iluminance were made in the plane of the windows of each elevation of the eleven-story building (Fig. 6).

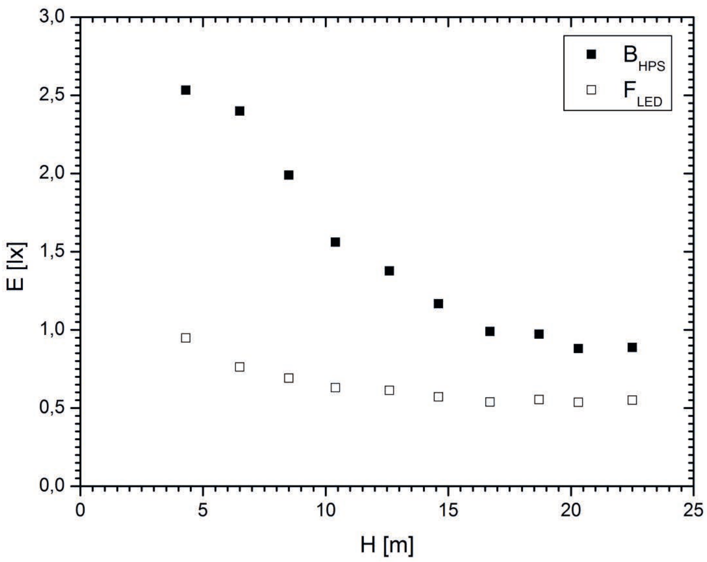

Fig. 6. The illuminance (E) in the plane of the windows of the apartment building above the pedestrian and pedestrian-driving route vs. height above ground (H). Filled points relate to lighting of the route before lamp replacement (B_{HPS} lamps), and empty points – after lamp replacement (F_{LED} lamps) (own elaboration)

Measurements were also taken in the middle of the pedestrian-driving route running parallel to the facade of the building along with a series of transverse transects (perpendicular to the facade of the building, from the lamp base to the building wall), both before and after lamp replacement (Fig. 6). It was found that before replacing the lamps with the B_{HPS} lamps, the illuminance of the centre of the pedestrian-driving route was 5–6 lx (depending on the individual lamp), but only 2–3 lx both directly under the lamps and near the wall of the building. After replacing the lamps, with F_{LED} lamps, it was found that the illuminance of the centre of the pedestrian-driving routes was 80–105 lx, 10–30 lx directly under the lamps, and 6-12 lx near the wall of the building.

6.4. Spectral analysis

The spectral analysis of all lamps identified in the Podwawelskie estate allowed us to state that in most cases, they are yellow, high-pressure sodium discharge lamps (HPS) with a CCT of approx. 2,100 K (in particular, all B_{HPS} lamps). Lamps based on light-emitting diodes (LED) are also common (especially in classes E_{LED-S} and E_{LED-E}). The CCT of these lamps is equal to approx. 4,500 K, which gives a colour similar to that of natural daylight. In one case, the use of a discharge lamp was found, in which the light source is an electric arc produced inside the bulb filled with mercury vapour (H_{MV}).

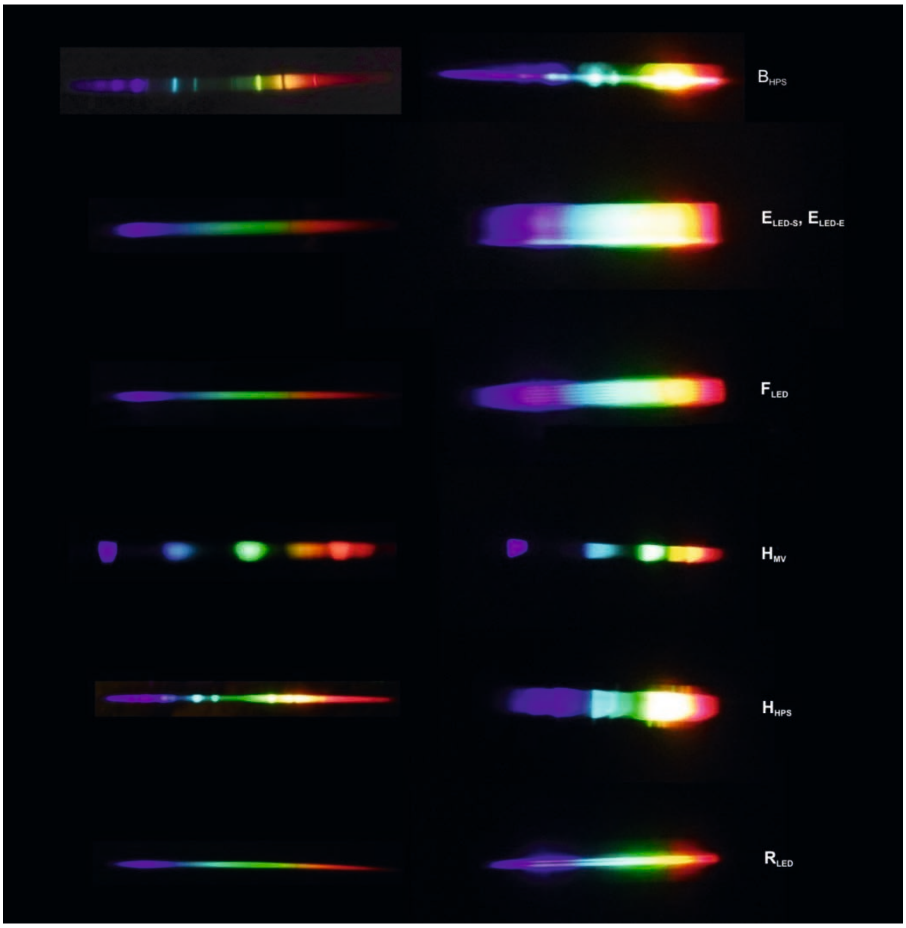

Fig. 7. Spectra of individual types of lamp identified at the Podwawelskie estate in Kraków (left: using a diffraction grating, right: using a spectroscope based on the Amici prism) (own elaboration)

6.5. Equidensitometry

A digital equidensitometry of the ground illumination was performed for all the described types of lamps (Fig. 8).

It was found that:

- the pavement lit by the B_{HPS} lamp is poorly and unevenly illuminated (in particular, the dark area at the base of the lamp is visible);
- a canopy over the entrance to the building casts a shadow over the area illuminated by the E_{LED-E} lamp;
- the building wall acts as a screen that reflects the light of the E_{LED-S} lamp;
- the H_{MV} lamp illuminates the ground insufficiently;
- F_{LED}, H_{HPS} and R_{LED} lamps evenly illuminate the ground.

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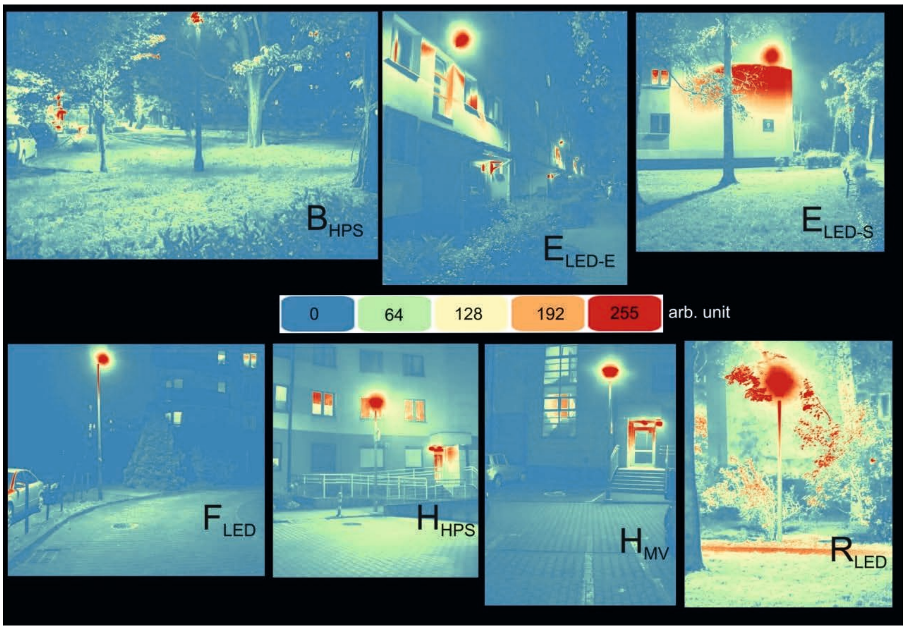

Fig. 8. Equidensitometry of lighting by individual types of lamps identified at the Podwawelskie estate in Kraków. Deep blue indicates the lowest brightness (0 arb. unit) and deep red relates to the highest brightness (255 arb. unit) (own elaboration)

7. Analysis of the results

The quality of lighting in any area must be considered in two aspects: its usability for humans and its impact on the natural environment.

The lighting of pedestrian and pedestrian-driving routes in the Podwawelskie estate in Kraków is not the dominant lighting in this area. Both the lamps themselves and the ground illuminated by them are not noticeable on the ISS image, while the streets and ground parking areas are visible. This observation is confirmed by the radiance values measured during the period with the lighting off (lockdown) in April and May 2020. While turning off the lighting of streets and parking lots caused a decrease in radiance by 53% compared to the value before this action, turning off the lighting of pedestrian and pedestrian-driving routes resulted in a reduction of radiance by only another 11% (the remaining 36% is mainly due to the safety lighting of important crossroads and various objects located in the measurement field). The brightness of the artificial sky glow is proportional to the radiance, so it can be assumed that the illumination of pedestrian and pedestrian-driving routes in the Podwawelskie estate has little effect on this category of light pollution. To verify this thesis, direct ground measurements of the surface brightness of both cloudless and overcast skies were taken. In the first case, it was found that after switching off the lighting of streets and parking areas, the luminance decreased by 39% compared to the value before this action, while after switching off the lighting of pedestrian and pedestrian-driving routes, it decreased by another 3%. With a completely overcast sky, after turning off the lighting of streets and parking areas, the luminance decreased by 47%, while there was no decrease in luminance associated with switching off the lighting of pedestrian and pedestrian-driving routes. As shown previously (Ścieżor, 2018), in the case of a cloudless sky, the sky glow is generated over a large area (with a radius of approx. 20 km), while in the case of an overcast sky with low clouds, the area of generation is much smaller (approx. 1 km). This means that in the first case, a significant part of Kraków is responsible for the reduction of luminance, while in the second case, it is related to an area similar to the Podwawelskie estate.

The difference between the percentage decrease in radiance and luminance of the sky glow of the cloudless sky is mainly due to the different mechanisms of light scattering into space and towards the ground (Ścieżor, 2020; Ścieżor, & Czaplicka, 2020). However, it can be stated with certainty that the lighting of pedestrian and pedestrian-driving routes in the Podwawelskie estate only slightly increases the brightness of the Kraków sky glow.

Among the other categories of light pollution, the possibility of glare and trespass should be considered. The glare effect was not found in any of the lamp categories illuminating the pedestrian and pedestrian-driving routes in the Podwawelskie estate. There is, however, the effect of lighting the windows of flats by the dominant HPS lamps with spherical covers (B_{HPS}). It was found that the illuminance of the walls of the apartment building by lamps of this type, placed near its facade, at a height of around 8 m (third floor), is still equal to approx. 2 lx, which amounts to a sevenfold increase in the illuminance provided by a full moon. In addition, the light of these lamps reflecting off the ceilings of apartments even at a height of 15 m (sixth floor) significantly interferes with the night darkness. After replacing these lamps with LED flat-cover lamps (F_{LED}), the illuminance at a height of 10 m (fourth floor) is already imperceptible against the background of the city's glow and does not exceed 1 lx at any level.

The usefulness of the analysed lamps in lighting pedestrian and pedestrian-driving routes is a separate issue. Of course, due to the unknown power of the light sources used, the comparisons must remain mainly qualitative. However, it should be noted that this power is usually imposed by the manufacturer of a given type of lamp, so the following observations can be generalised to other such light sources found in other housing estates in Kraków.

The ball-shielded sodium lamps (B_{HPS}) do not fulfil their purpose to a very large extent. The illuminance of the area illuminated by them does not exceed 5 lx, which is too low a value to maintain a sense of security and does not comply with the requirements for pedestrian walkways contained in the PN-EN 12464-2: 2014 standard (min. 5 lx). In addition, the way these lamps are mounted means that there is a shadow zone with very poor lighting directly below them. Slightly better are the lamps of the same type, but with a differently constructed cover and a canopy (H_{HPS}) providing an illumination of 15 lx at the ground. Additionally, they are not burdened with the aforementioned shadow effect. In one case, a high-pressure mercury lamp (H_{MV}) was found mounted in an identical holder as the H_{HPS} lamps. This lamp not only emits light with much too low an intensity (only about 3 lx) but also poses an ecological threat in the event of damage (mercury vapour).

In the case of lamps based on LED technology, both the assembly and the luminaire are extremely important. In the Podwawelskie estate, this type of lighting was used in the case of free-standing lamps with a flat socket (F_{LED}), free-standing lamps with the brim-like luminaire (R_{LED}) and facade lamps mounted on the walls of residential buildings (E_{LED-S} and E_{LED-E}). The best lighting is provided by F_{LED} lamps, which illuminate surroundings uniformly with illuminance equal to approx. 100 lx, at the same time, minimally trespassing upon the vicinity. The covers and the housings of R_{LED} lamps make the light emitted by the LED panel largely shielded and, as a result, illuminates the ground with illuminance equal to only about 10 lx. In addition, some of the light escapes through the opening at the top of the luminaire, heading mainly towards the zenith. In the case of facade lamps, E_{LED-S} lamps mounted on the side walls of buildings completely fulfil their functions. The light of these lamps is not shielded in any way, in addition, the wall below serves as a screen that additionally illuminates the pavement at a distance of approx. 3 m. In this case, the illuminance reaches 30 lx, which is completely sufficient to ensure the safety of passers-by. Unfortunately, identical lamps on the front elevations of the buildings were installed above the canopies protecting their entrances. As a result, in the event of a failure of the LED information panel, just in front of the entrance, the illuminance is equal to only 0.5 lx near the entrance, and just behind the canopy shadow area, on the pavement running along with the building, it rapidly increases to 20 lx. The resulting contrast is undoubtedly a threat to people leaving and entering buildings and generates light pollution in the glare category. Furthermore, the illuminance of the pedestrian-driving route running a few meters further is only about 8 lx, which does not meet the requirements for "traffic areas for slowly moving vehicles" contained in the PN-EN 12464-2: 2014 standard (min. 10 lx).

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8. Conclusions

The lighting of pedestrian and pedestrian-driving routes in the Podwawelskie estate undoubtedly needs to be corrected. While, in its present form, it does not generate light pollution in any of its existing categories, it often does not fulfil its basic function, which is to illuminate the aforementioned routes. To improve the quality of lighting, it would be necessary to:

- remove all existing B_{HPS} lamps and replace them with either R_{LED} lamps (where they function as park lamps) or F_{LED} lamps (where their main function is to illuminate pedestrian and pedestrian-driving routes). If it is possible, the surface of these routes should also be replaced with one that would reflect the light of these lamps to a lesser degree. It should also be remembered that the mounted LED lamps should have a light colour similar to daylight (i.e. with a CCT of at most 4,000 K);
- additionally illuminate the area under the canopies at the entrances to the buildings, while maintaining the E_{LED-E} type facade lamps;
- trim vegetation, often completely shielding the light of lamps installed in its surroundings during the growing season;
- cover lamps from the window side with a non-transparent luminaire (in the case of free-standing lamps illuminating the facades of buildings).

After such a correction, the Podwawelskie estate, remaining a housing-park estate, will also be friendly to residents at night, strengthening both the sense of security against criminals and wild animals (more and more frequent incursions of wild boars), as well as ensuring the comfort of sleep.

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