Artificial light emission analysis for the city of St. Petersburg

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Abstract. Artificial light emission within the limits of major cities is increasing year by year. The level of this rapid growth depends on the influence of complex factors such as urban enlargement, air pollution, environmental conditions, lack of outdoor lighting master-planning, etc. Continuing monitoring of sky glow changes is an important part of the lighting environment's complex analysis. This paper estimates the contribution of 18 districts of St. Petersburg to the glow between 2014 and 2017, evaluated with the use of Garstang's model and GIS-based analysis of VIIRS data. The dynamic changes in sky brightness show a significant increase in the anthropogenic sky glow over three years.

1 Introduction

The influence of urban lighting on night sky brightness has been studied since 1970s. The first model for a sky brightness estimation was Walker's model [1]. Walker's law is described by the equation (1), considering the population size and the distance of the observer from the city.

$$B = CPD^{-2,5} \tag{1}$$

where P is the population, D is the distance of the observer from the city, B is an increase in the sky brightness related to natural sky glow, and C is the coefficient dependent on such factors as light emission per capita and the reflection coefficient of the ground surface.

A more complex model of sky brightness estimation, which took into account the approximation for small angles and considered the mechanisms of particle dispersion, was proposed by Bertiau and Treanor [2]. Treanor's model was modified by Garstang [3,4,5] to consider the heterogeneity of the atmosphere. In the modified model, the density of molecules and aerosols in the atmosphere exponentially decreases with altitude increase. Garstang's model showed itself as responsive in many American observatories. Since 2001, satellites have been used to analyse artificial night sky brightness. This research was first published by P. Cinzano, F. Falchi and C. D. Elvidge.

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The problem of artificial light emission growth has traditionally been tackled by astrophysicists and astronomers. Yet experts from other related fields have been lately paying increasing attention to this problem.

From the lighting design perspective, artificial light emission analyses are very important to monitor annual augmentation in order to protect the environment from the further growth of sky glow caused by artificial lighting in the cityscape. This is especially important for countries without control over the minimization of light pollution.

2 Field of study

Despite the importance of limiting artificial light emission, this question has not been sufficiently studied in Russia. A lack of specific requirements, which would limit and regulate the work of lighting designers, amplifies the problem.

Figure 1. An example of a low-quality lighting solution.

Figure 2. Luminance distribution, measured by using a luminance measuring imaging photometer.

Changes in the number of light fixtures between 2014 to 2017 is shown in Table 1.

Table 1. The number of light fixtures (Data source: State Unitary Enterprise Lensvet)

Year	Number of fixtures	Number of poles	Objects with arch. lighting
2014	215319	78508	427
2017	257600	97696	445

Table 2. The share of light fixtures in 2017 (Data source: State Unitary Enterprise Lensvet)

Types of light sources	% of the total	% of capacity
HPS lamps	65.4	87.6
Metal halide lamps	26.6	10.3
LED lamps	8.44	1.94

The number of lighting fixtures grew by 42,000 units between 2014 and 2017. In view of these significant changes, the analysis of dynamic artificial light emission is of utmost importance.

In the Russian Federation, there are no laws, codes or standards, which would regulate light pollution. The number of buildings and constructions with architectural lighting in big cities in Russia is very high, compared with European countries. To raise the issue of light quality, we evaluated sky glow progression in the period between 2014 and 2017.

3 Methodology

In our study, we used artificial sky brightness modelling principles formulated by Garstang. In total, 18 districts of St. Petersburg were considered separately and included in the research study.

Garstang's model offers a two-component composition of the atmosphere [4,5]:

- molecular components of the atmosphere, which particle density at h height above the sea level is described by the equation:

$$N_1(h) = N_m \cdot e^{-c(h)} \qquad (2)$$

where $N_m = 2.55 \cdot 10^{19}$ sm^3 *is the particle density at sea level,* $c = 0.104$ km^{-1} *according to Allen*

- aerosol particles, which density at h height is:

$$N_2(h) = N_a \cdot e^{-a \cdot h} \qquad (3)$$

where $N_a = 2.55 \cdot 10^{19}$ sm^3 *is the density of aerosol particles at ground level,* $a = 0.657 + 0.059K$ *is the approximation based on McClatchey data, K indicates the quality of the atmosphere. [4,5]*

The equations 3 and 4 may be used with the following assumptions:

- molecules in the atmosphere are in hydrostatic equilibrium
- density of aerosol is the exponential function

● the atmosphere is horizontally homogeneous

The absorption in the lower layers of the atmosphere for vertical distribution of particles is represented by the Lambert-Beer law.

$$\tau(h) = \int_0^h k dh = N_m \cdot \sigma_m \cdot [(1 - e^{-ch})c^{-1} + 11.778K(1 - e^{-a'h})] \quad (4)$$

where $k = N_m \cdot \sigma_m + N_a \cdot \sigma_a$, σ_m *is cross section of the molecules,* σ_a *is cross-section of aerosol particles.*

The model considers Rayleigh scattering of molecules in the atmosphere with the cross-section of $\sigma_R = 4.6 \times 10^{-27} sm^2$ for the 550 nm wavelength for visible observations. Multiple scattering of molecules and aerosol particles is described by the equation:

$$SAA(\omega) = N_m \sigma_m (11.778K \frac{\{1 - e^{-ascos\,\psi}\}}{a} + \gamma \frac{\{1 - e^{-cscos\,\psi}\}}{c}) cos\,\psi^{-1} \quad (5)$$

where γ is the Garstang factor to account for the spherical nature of Rayleigh scattering compared to aerosol scattering [4,5].

According to Garstang's model, artificial light emission intensity distribution in the upper hemisphere is described by the equation:

$$I_{up} = \frac{LP}{2\pi} \cdot \{2G(1 - F) \cdot cos\psi + 0.554 \cdot F \cdot \psi\} \quad (6)$$

where G is the surface albedo, F is the proportion of the luminous flux emitted by light fixtures into the upper hemisphere, P is the population, L is luminous flux per capita.

Luminous flux per capita was estimated based on statistical data on lighting equipment provided by State Unitary Enterprise Lensvet. The population size of 18 districts was evaluated in accordance with Federal State Statistics Service data.

In the equation (6), the albedo of the earth's surface was set G=0.15, and the proportion of the luminous flux emitted by lamps into the upper hemisphere is F=0.13.

The basic equation of the sky brightness model is:

$$b = \pi \cdot I_{up}(\psi) \cdot S^{-2} \cdot \int du \cdot e^{-\tau(s)} \cdot (1 + SAA) \cdot e^{-\tau(u)} \quad (7)$$

The formula for the transition to photometric units, accepted in astronomy, is as follows:

$$V = 41.438 - 1.0857 \cdot ln(b) \quad (8)$$

For GIS-based analysis, we used different layers of information about St. Petersburg, such as residential population data, Visible Infrared Imaging Radiometer Suite (VIIRS) data on radiance provided by the Earth Observation Group, and National Geophysical Data Center (NOAA) collected by Jurij Stare.

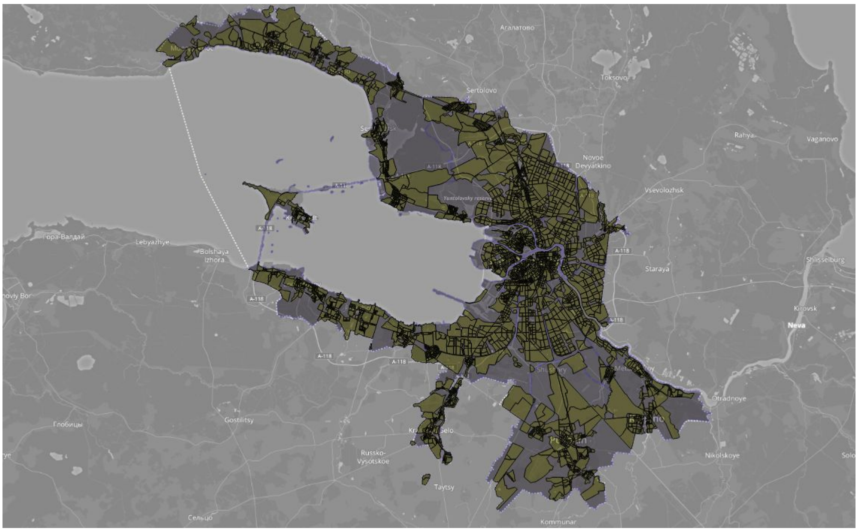

Figure 3. The residential population data layer.

4 Results

The largest contribution to the increase in the sky brightness in St. Petersburg is made by the following regions: Kalininsky, Primorsky, Vyborgsky, and Nevsky.

The artificial light emission data obtained for all districts are shown in Figure 4 and Table 3.

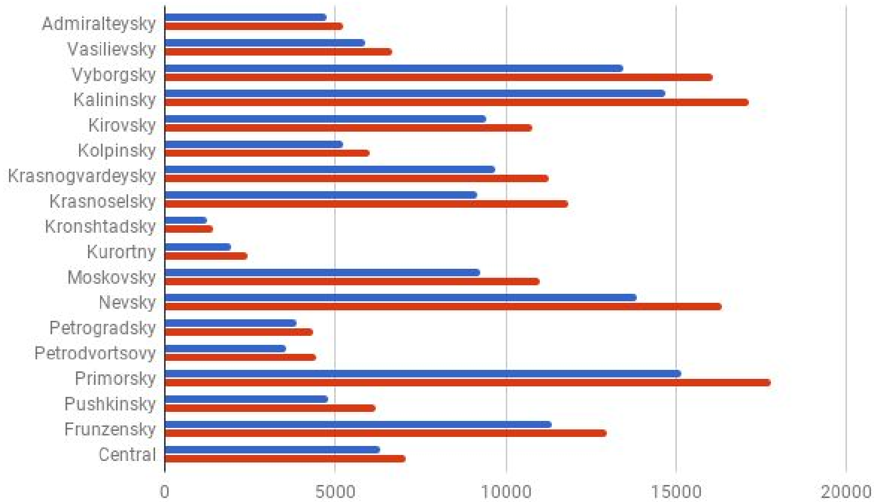

Figure 4. The artificial light emission data obtained for all districts of St. Petersburg based on Garstang's model for the years 2014 (blue bars) and 2017 (red bars).

Table 3. The population and artificial light emission intensity for 18 districts of St. Petersburg.

District	2014		2017	
	P, thousands of	I_{up} , cd	P, thousands of	I_{up} , cd

	people		people	
Admiralteysky	171	4762	164	5242
Vasilievsky	211	5875	209	6694
Vyborgsky	483	13449	502	16096
Kalininsky	527	14674	536	17134
Kirovsky	339	9439	337	10776
Kolpinsky	187	5207	188	6003
Krasnogvardeysky	348	9690	352	11250
Krasnoselsky	330	9189	370	11833
Kronshtadsky	44	1225	44	1423
Kurortny	70	1949	76	2434
Moskovsky	333	9272	344	11006
Nevsky	498	13869	512	16368
Petrogradsky	139	3870	136	4340
Petrodvortsovy	128	3564	138	4420
Primorsky	544	15147	556	17772
Pushkinsky	172	4789	193	6182
Frunzensky	408	11360	406	12993
Central	227	6320	220	7047

The results of the GIS-based analysis for the period between 2014 and 2017 are shown in Figure 5 and Figure 6.

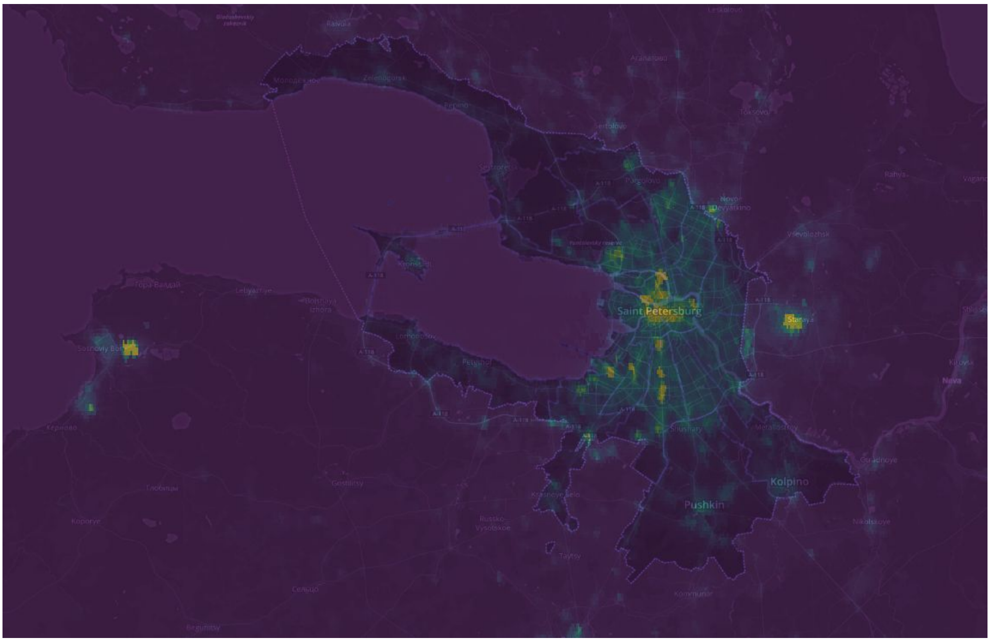

Figure 5. Artificial light emission data obtained for all districts of St. Petersburg based on 2014 statistical data.

Figure 6. Artificial light emission data obtained for all districts of St. Petersburg based on 2017 statistical data.

5 Conclusion

Artificial light emission is growing very rapidly without any codes or laws which would help minimize light pollution. The attention of lighting designers should be focused on the quality of their work.

According to the definition of the Institution Lighting Professionals (ILP), any artificial light, which goes beyond the limits of the subject to illumination, including the light projected above the horizon into the night sky or creating glow danger, is considered undesirable and causes light pollution.

At present, some countries such as the Republic of Chile, Slovenia, Italy, the Czech Republic, parts of the United States of America and the United Kingdom have adopted a series of regulatory documents with the aim to reduce the anthropogenic component of sky glow.

To reduce the dynamics of the growth in anthropogenic component of sky glow, patterns of light propagation in the lower layers of the atmosphere and scattering type of various particles should be considered while design works. The reflected component of the light flux from the surfaces to be illuminated contributes significantly to sky glow. Therefore, light pollution can be reduced by optimizing the design of lighting systems, ensuring their compliance with acceptable levels of quantitative characteristics of lighting, performing installation control, and using lighting control systems.

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