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Research Paper

The Indication Methods and Techniques of Urban Light Pollution

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Abstract
The goal of this study is to review and categorize approaches and methods of facing urban light pollution. Probing various references and documents, the current practice focus on extracting and reviewing different types of urban light pollution detection, survey, and measurement to define a taxonomy of methods by instant comparison. The means of measurement and detecting this pollution include 14 most cited techniques that have been classified in four categories in this paper. These methods comprise ground-based surveys, aerial surveys, remote sensing, and city modeling. Finally, this paper represents a framework of the methods to show how and when they should be employed considering the pros and cons of each one of these methods. By creating a foundation of specialized arguments, this study helps researchers and urban designers to complete urban lighting research and design. In addition, it provides base information for the analysis of urban light pollution.

Keywords: *Light pollution, Urban pollution, Indication method, Urbanism.*

1. INTRODUCTION

An urban area is defined according to its psychological and health effects on the citizens (Mohammad Moradi et al. 2013) (Mahlabani et al. 2011). Living in modern cities has caused fatigue and mental health problems (Najafi et al. 2015) (Behzadfar et al. 2014). Urban light pollution is a proliferating form of pollution originated from cities. It is a side effect of the presence of human-made light at night (Khakzand and Azari, 2014). Thus, it is our duty to prevent further damages caused by this new shape of pollution which widely affects the environment, creatures' lives, and human beings in an urban setting (Table 1). By bringing new sources of light, we have disabled ourselves to see other natural celestial sources of light. Only since the 1970s, astrophysical research on this matter began to commence (Aube, 2015). So, there is an urgent need for research in this field that not only considers negative effects of urban artificial light, controlling light pollution, and urban studies, but also focuses on providing a foundation of light pollution information for other fields of study concerned with urban pollutions. In this sense, the aim of this paper is to prepare base information on methods by which urban light pollution would be indicated and measured. (Faizi et al. 2015)

Before any design in an urban context, a designer should be fully aware of the possible drawbacks of his master plan. Urban light pollution is one of the unwanted outcomes of urban design that should be taken into consideration. Therefore, one of the aspects that an urban designer should consider regarding the lighting at the first stages of the design is the analysis of the current condition of the lighting. Usually in urban contexts, light pollution is distinguished into three shapes (Fig. 1). Based on the methods that would be discussed in the following

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sections, the urban designer should analyze the context of design with site inspections, luminance recording, and simulation before creating the regulations (Diagram 1). Therefore, the focus of this research is on the analysis part of the roadmap of urban design regarding urban light pollution. Pothukuchi in his paper (Pothukuchi, 2021) has defined an 11-steps policy of best practices for outdoor lighting to reduce light pollution. His steps aim to define a regulation for urban lighting designers ranging from the specification of the purpose of lighting to the instructions about the inventory of luminaires and how to reduce the total installed flux. Azari and Khakzand (2014) have studied a method of lighting design which is referred to as space syntax. In their study, they propose this method by emphasizing the importance of dark sky and nighttime tasks with the approach of mitigating the light pollution. The flowchart of their space syntax method starts from the design scenario and ends up with the design strategies. For context-oriented lighting design strategies, it is highly required to base one part of the design scenarios on the importance of the analysis of light pollution. However, the focus of this article is not to review regulations or measures, but to create a comprehensive understanding of the methods of urban light pollution monitoring, and how and where to apply these methods for the analysis stage.

Table 1. The Negative Effects of Urban Light Pollution on the Environment, Humans, and Animals

Urban contexts	The improper use of the floodlights or angle of light bulbs could result in demeaning effects on cultural heritage
	Possible drawbacks for aesthetic values of the urban components and undesired change in the context due to excessive light pollution caused by a flaw in lighting design
	Trespass, glare, and clutter are the three troublesome effects of inappropriate lighting design which might lead to unhealthy night city
Human and society	Night sky aesthetics
	The invisibility of celestial objects damaging astro-tourism and astronomers' interest
	Physical and physiological effects on human
	Relationships between artificial light emissions and insomnia and even cancer
	Economical damage caused by extravagance in lighting
Animal life	Serious damages to survival ability and animal breeding
	Changing offspring and nurturing circle of aquatics
	Disrupting migration pattern of birds through which thousands of them would die annually
	Disturbance in some small mammal's activity time
	Disturbance in the relationship between prey and predator
Environment	Energy consumption and releasing green gases
	Plant's disability in coping with seasonal changes
	Plants' growth interruption
	An increasing form of environmental pollution

Source: Adapted from (International Dark Sky Association 2015); (Chepesiuk, 2009); (Deangelo, 2013); (Zeini Aslani et al. 2021); (Goronczy, 2020)

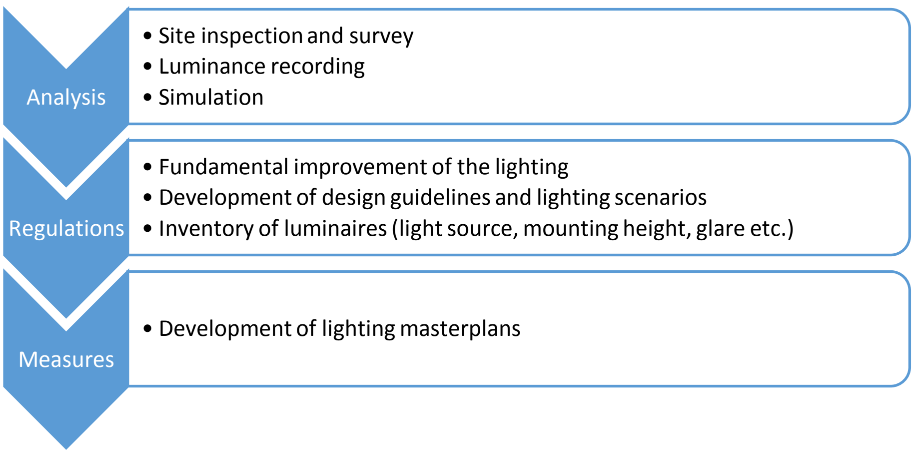

Diagram 1. Development of the roadmap of urban design regarding light pollution (Adapted from (Goronczy, 2020))

This study through a review approach tries to extract all known methods of urban light pollution indication across various references so far and make an instant comparison among them to define a taxonomy that has not been done before. This pollution comprises three factors which are sky glow, light trespass, and glare (Rensselaer Polytechnic Institute, 2007), each of which can be identified and measured by allocated methods. There are also methods through which all three or two aspects of light pollution can be indicated. Fourteen various methods in this regard, including direct observation, experimental measurement of sky quality, measurement of ambient illuminance intensity, the experimental device of sky glow description, EF, ILLUMINA, OSP, Optimal Linear Regression Function, DMSP remote sensing, VIIRS remote sensing, ISS imagery, EROS remote sensing, aerial survey, and city modeling have been introduced in four sections of Ground-based Survey, Aerial Survey Remote Sensing, and City Modeling. Furthermore, this research creates a taxonomy of these methods based on an instant comparison.

2. GROUND-BASED SURVEY AND IN SITU MEASUREMENTS

2.1. Direct Observation

The primary and simplest way of light pollution estimation is direct observation in which the number and quality of visible stars and other celestial objects would be the reference for assessment. One approach is expressed by Rensselaer Polytechnic Institute (2007) where they introduce the Big Dipper constellation as a counting source for the number of visible stars to the naked eyes. Another way has been defined by Kollath as “the number of observable stars in a fixed region of the sky” (Kollath, 2010). The Bortle dark-sky scale in categorizing night-sky modes has been employed widely for this purpose (Table. 2) (Fig. 2). Since the only instrument of this method is the eyes, its accuracy is highly dependent on the eye health of the observer (a vision close to 20/20 vision is required). Star-photometer is a device dedicated to direct observation through which the naked eye of the observer would be equipped by the device for more precise observations.

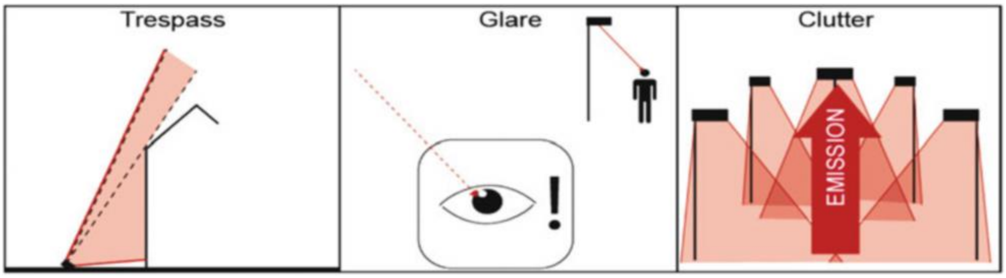

Fig 1. Pictorial Representation of Three Forms of Urban Light Pollution (Source: (Goronczy, 2020, p.6))

Table 2. Bortle dark-sky scale description

Level	Name	Color	Limiting magnitude	The degree of artificial lighting (by false color)	Description
1	Excellent Dark Sky Site	Black	7.6-8.0	<11%	M33 (the Pinwheel Galaxy) is an obvious object, and the brightness of Jupiter and Venus is annoying to night vision. Ground objects are barely lit and trees and hills are dark.
3	Rural Sky	Blue	6.6-7.0	11–33%	Globular Clusters are distinct, but M33 is only visible with averted vision, M31 (the Andromeda Galaxy) is obviously visible, furthermore, some light pollution is evident along the horizon, and ground objects are vaguely apparent.
5	Suburban Sky	Orange	5.6-6.0	1–3%	Milky Way appears washed out overhead and is lost completely near the horizon, and Light pollution domes are obvious to casual observers. Ground objects are partly lit.
7	Suburban/Urban Transition	Red	5.0	3–9%	MW is totally invisible or nearly so. The entire sky background appears washed out, with a grayish or yellowish color.
9	Inner City Sky	White	4.0	>9%	only the Pleiades Cluster is visible to all but the most experienced observers, and the entire sky background has a bright glow, even at the zenith

Source: (The Bortle Dark-Sky Scale 2012); (Bortle, 2001); (Goronczy 2021, p. 9)

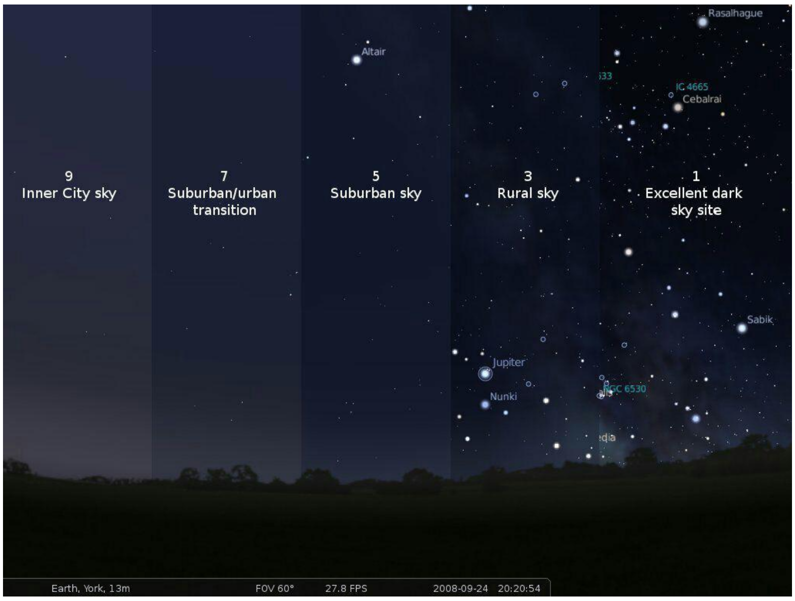

Fig 2. Light Pollution Rating in the Direct Observation Methodology (Source: http://stellarium.org/img/screenshots/0.10-bortle.jpg)

2.2. Experimental Measurement of Sky Quality (SQM)

Ground-based and aerial-based measurements are the two major ways of light pollution monitoring (Shariff et al. 2016). Being affordable, convenient to use, and handy, the Sky Quality Meter (SQM) is a facilitator for measuring sky brightness from the ground. Three models of this device include SQM-L, SQM-LU, and SQM-LE; the first one is suitable for making a map by measuring sky from a grid of points, while the other two are employed for monitoring purposes in fixed positions (Sanchez de Miguel, 2015). Since the environment is having a changing color spectrum due to the various atmospheric aerosol contents, clouds, the extinction of artificial lightings in the sky, moon phases, solar activity, and coordinates of zenith angle correlated to a specific region on earth, we would be able to calculate synthetic photometry for different spectral sources and bands through calculations for measuring AB magnitudes and converting them into radiance (Sanchez de Miguel et al. 2017).

To avoid mistakes in reading SQM magnitudes, users should be aware of the color of luminaires (this device is blind to colors). They also should be aware of the vision in which they observe the sky since these appearing magnitudes accord themselves with accidental direct beams of the luminaires. In addition, readings are lower than real scotopic vision; in this sense, a color-sensitive device (color sensor or multiband camera), as well as Naked Eye Observation technique, are highly recommended as complementary tools for SQM in places with high color-changing rates (Sanchez de Miguel et al. 2017). Furthermore, in some illumination sources with the bluish component in their spectra, like LEDs, the reading shows a lower magnitude than real human vision. Thus, to get an accurate measurement, users should train themselves in interpreting SQM readings or employ astronomical filters for their device (Sanchez de Miguel et al. 2017).

To determine the magnitude of natural sources, users can use the following equation (Eq. 1), where SB is the surface brightness, and D is the angular FOV of the SQM:[1]

$$m_{SQM} = SB - 2.5\log\left(\frac{\pi D^2}{4}\right), \text{ (Eq. 1)}$$

Source: (Sanchez de Miguel et al. 2017)

Another major benefit gained from this method is measuring sky glow from land by which the need for a satellite in some limited areas has been rectified while the accuracy is still higher than average.

2.3. Measurement of Ambient Illuminance and Luminance (Lux-meter, Luminance-meter, Digital Camera)

As explained in the previous section, SQM measures sky brightness (sky glow), but there is also a demand for instruments measuring trespass and glare in the smaller areas. Another ground-based instrument is the 'Lux-meter' by which ambient illuminance intensity and light trespass would be measured. Equipped by an internal memory for storing data measured in lux (or cd/m^2), Lux-meter possesses a calculator software for further analysis, as well as various interfaces for computer interconnection (Lux meter, 2015). Besides, 'Luminance-meter' and 'digital camera' by having the ability of brightness assessment in a luminaire are capable of measuring glare in candela per square meter (Hiscocks, 2014).

Through measuring illuminance (E) and by the awareness of reflectance value (ρ) of the area, in the right conditions, luminance (L) can be achieved (Eq. 2).

$$L = \frac{E\rho}{\pi}, \qquad \text{(Eq. 2)}$$

Source: (Hiscocks and Eng, 2011)

They can be utilized for measuring the quantity of light pollution of ambient like the open area of a facility, or a passage. Furthermore, these instruments, by which trespass and glare from any direction with high accuracy would be measured, can be combined with SQM to assess all three aspects of light pollution from the ground.

2.4. The Experimental Device of Sky Glow Description (DSLR Camera)

Digital Single Lens Reflex (DSLR) cameras are being used widely for night brightness study owing to low expenditures, easy access, satisfactory dynamic range, and adequate spatial resolution. When the camera is equipped with a fisheye lens, a thoroughgoing calibration for the DSLR camera is necessary. Lack of a certain RAW format for the data achieved by this method is its principal drawback; therefore, there is a need to alternate the RAW data to normal data which can be made through software such as DCRAW. Each pixel of the imagery should be calculated individually to gain the luminance of each unit of the picture in the new intended format (Lamphar and Kocifaj, 2016). The image taken by this instrument after being converted to false-color images would illustrate the luminance distribution of the sky (Fig. 3) (Kollath, 2010). However, by the development of Rhino software plugins and the cutting-edge DSLR cameras, the false-color image could be created with Honeybee in Grasshopper plugin out of HDR image formats. Therefore, the sky in this method should be captured by different exposures to create an HDR image. Afterward, the HDR false-color output could be converted into TIF format by the same software.

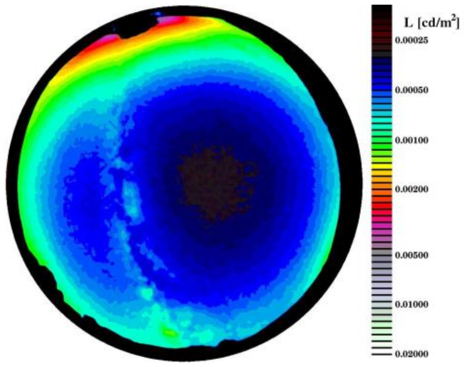

Fig 3. Luminance Distribution of a City (Located at the Top) using an Image Captured by DSLR Camera and Processed by DCLUM Software

Source: (Kollath, 2010)

Prerequisites of this method to create the photo of sky glow in a specific city or area, as have been cited in references mentioned above, are DSLR camera, photometric sensor, portable computer, and software calculations which undergoe the process of Python and Grasshopper software. This method could also be used to identify the average luminance levels (cd/m^2) in the urban realm to analyze the luminance captured from urban surfaces such as roadways and facades (Fig. 4).

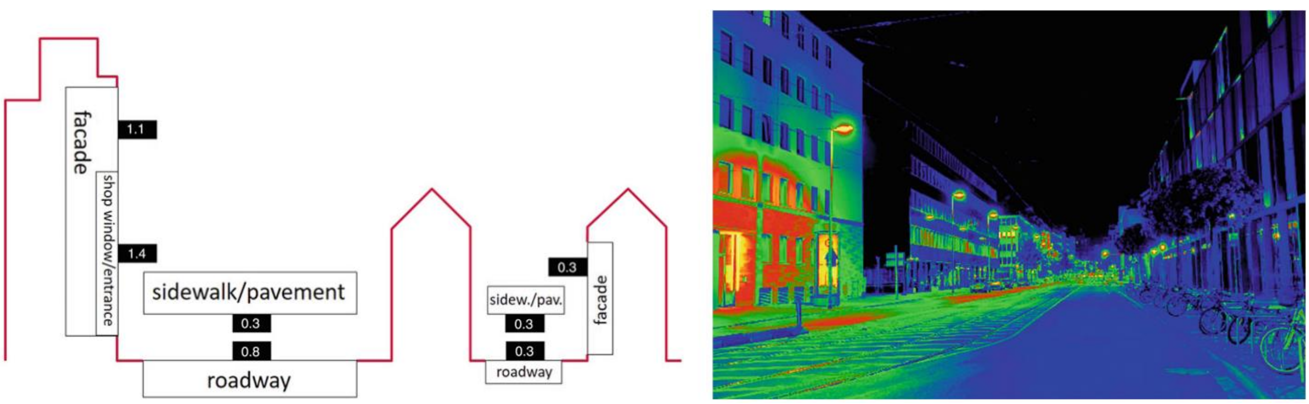

Fig 4. A Street in Boston City that have been Analyzed with the False-color Image

Source: Goronczy, 2020, p 118

2.5. Experimental Determination of Emission Function (EF)

Each city worldwide has a particular bulk emission function of diffused artificial light or emitted and reflected upward light from luminaires across it. The first approach of this method is to calculate this emission function through specialized algorithms and then to delineate the light pollution pattern of the city. The primary EF is Garstang's model (GEF) which takes advantage of easy calculations. However, it is abolished due to some drawbacks such as incorrect simulation of near horizon emissions (Lamphar and Kocifaj, 2016), and secondly due to the advent of City Emission Function (CEF). Below, the operation of GEF is represented (Fig. 5) (Eq. 3).

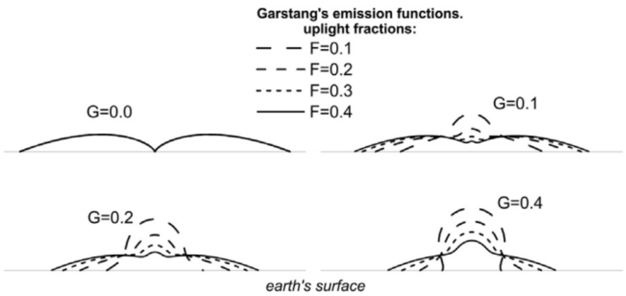

Fig 5. A City Pattern of its GEF. F Represents the Upward Light, Whereas G is the Reflected Light
Source: (Lamphar and Kocifaj, 2016)

By employing Equation 3, the angular distribution of emitted light would be assessed; where L and P are the per capita visible light output and the population, respectively:

$J_y(z) = \frac{LP}{2\pi}\left[2G_y\left(1 - F_y\right)\cos z + 0.554\, F_y z^4\right]$, (Eq. 3)[2]

(Source: Lamphar and Kocifaj, 2016)

It is not possible to obtain EF via satellite and aerial imageries because satellites cannot cover all emission angles, and aerial imagery is both expensive and is not designed for this purpose[3]. Therefore, bulk emission function would be achieved through ground-based surveys (usually DSLR camera and SQM) from several points at the city edges using empirical formulas (Kocifaj, 2017). The radiant intensity function $CEF(z_E)$ can be acquired as a function of ground radiance $I(z_E)$ (Eq. 4)[4]:

$CEF(z_E) = I(z_E)\cos z_E$, (Eq. 4)

Source: (Kocifaj, 2017)

2.6. Light Pollution Modeling in a Heterogeneous Environment (ILLUMINA)

An approach to model light pollution is to measure Aerosol Optical Depth (AOD) of the sky. For this purpose, several methods and instruments have been developed including sun-photometer, star-photometer, and inversion algorithms in remotely sensed images (Aube et al. 2005). ILLUMINA is an advanced method in this regard in which a Spectrophotometer for Aerosol Night Detection (SAND) would model the light pollution of a case study. Then by simulating specific measurements of reflected, scattered, and directed beams from a source to any vortex of the gridded atmosphere, the best possible AOD magnitude through a trial-and-error approach will be calculated (Fig. 6) (Aube, 2015).

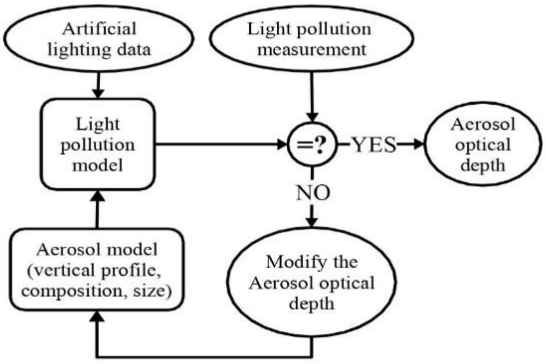

Fig 6. The Trial-and-error Process of ILLUMINA Methodology

Source: Aube, 2015

There is a scenario for the measurements of every voxel in the space exposed to artificial light emitted from a luminaire. It consists of four beams[5] leaving the luminaire and crossing at a voxel located along the sight line of the spectrophotometer (Fig. 7). Therefore, this method's operation is like that of ray-tracing software (Sanchez de Miguel et al, 2017). I_{no}, the light spectral intensity (W/str/nm) received by the spectrophotometer, is a combination of the four beams:

$I_{no} \approx I_1 + I_{r1} + I_2 + I_{r2}$, (Eq. 5)

(Source: (Aube et al, 2005))

Next, the total spectral flux (Watt/nm) scattered toward the spectrometer can be calculated using:

$\Phi_m = \sum_n I_{no}\,\Omega_{no}\frac{\Omega_{on}}{\Omega_{FOV}}$, (Eq. 6)

(Source: (Aube et al, 2005))

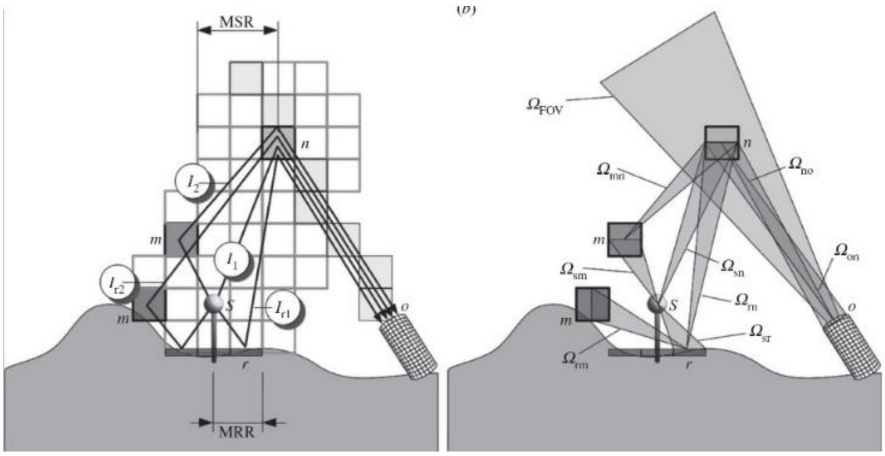

Fig 7. Simulated Measurements of ILLUMINA
Source: (Aube, 2015)

Three ways in sky light diffusion that account for the light pollution in the environment have been defined as direct illumination, light scattered by clouds, and scattered light from a clear sky (Aube, 2015). Due to the disability of computing and modeling light scattered by clouds in the ILLUMINA method and the trivial impact of direct illumination on light diffusion in the sky, now this method only is available to model the third way of sky light diffusion and would calculate it (the ability of modeling light scattered by clouds in this method is ongoing) (Aube, 2015). The presented method can be employed by built environment designers to manipulate luminaires' height, type, cutoff, cover, etc. for achieving the best position and condition of lighting.

2.7. Outdoor Site-lighting Performance (OSP)

The logic of this method (Brons et al. 2008) is based on the measurement of the main attributes of light pollution (i.e. sky glow, light trespass, and glare) through creating a hypothetical frame box with each side placed on the line boundaries of certain property (OSP is also applicable for roads and various sites) (Fig. 8). The top surface is standardized upper with a difference of 10 meters from the highest luminaire. Furthermore, this computational model requires software capable of computing inter-reflections in the box. Each surface of this box contains a regular set of points on it from which the software would measure the amount of light in units of illuminance (lx). This unit is a standard unit for illumination interpretations because of various reasons. Regarding the size of the property, these points are embedded in each surface with every point fixed lesser than 2 meters from the nearest surrounding points. Equations 1, 2, and 3 show how to measure average 'sky glow' (SG), 'light trespass' (LT), and 'discomfort glare' (DG) using OSP. DG value represents the amount of light for someone looking directly to the luminaire under the study and possesses a more complicated formula than the other two. This method has been performed since 2005 by scientists in Rensselaer Polytechnic Institute (Architectural Lighting Staff, 2008).

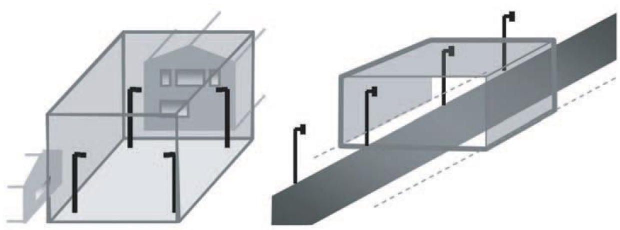

Fig 8. Calculation Boxes for Lighting Installations (Left: Car Park; Right: Roadway)
Source: Brons et al. 2008

Using the box, the three abovementioned aspects of light pollution can be calculated through the following equations (Eq. 7, Eq. 8, and Eq. 9); where E_l, E_s, and E_a, are: the produced illuminance at the property line from the intended luminaire, the produced illuminance at property line by the surrounding luminaires of the intended luminaire, and ambient illuminance (without artificial lighting), respectively (Brons et al. 2008. These magnitudes can be achieved by software or other standard light measurement instruments.

$$SG = \frac{illuminance\ on\ side\ planes\ (lx) + illuminance\ on\ top\ plane\ (lx)}{total\ area\ of\ all\ planes}$$
, (Eq. 7)

$LT = maximum\ illuminance\ on\ each\ side\ plane\ (lx)$, (Eq. 8)

$DG = \log(E_l + E_s) + 0.6 \log\left(\frac{E_l}{E_s}\right) - \log(E_a)$, (Eq. 9)

(Source: (Brons et al. 2008))

Methods like direct observation or nighttime photographs cannot provide precise data from which one can design lighting installations, whereas OSP seems to be an appropriate approach for this purpose. On the other hand, since OSP is practicable in a restricted site, it does not consider aerial factors contributed to light pollution, namely aerosol content, droplets, and other attributes in the atmosphere. Therefore, it does not perfectly address sky glow over a region or city. Besides, employing this box over a larger site like a city for measuring sky glow is almost impractical because of the enormous time spent in software computations. Despite these, OSP is a perfect method in measuring light pollution in fine-scale facilities with considering the three aspects of light pollution. In these situations, the amount of sky glow is highly reliant on the ceiling of the box (Brons et al. 2008). ILLUMINA can be a complementary method for OSP to eliminate its defect in neglecting aerosols.

2.8. Optimal Linear Regression Function

This method which is introduced by Estrada-García (Estrada-Garcia et al. 2016) consists of a computing approach in which a regression function model comprised of six different variables (including luminaire type (t), fill factor[6] (f), street width (w), luminaire height (h), building height (b), and the reflectance of the walls (r)) would predict and delineate the lighting structure in a specific case study. This technique calculates the fraction of Urbanized Upward Flux (UUF) over Total Installed Flux (TIF) which is the predicted fraction of up light (Fig. 9). Since the values of t, f, w, h, b, and r, as well as the coefficients (a_1, a_2, etc.), vary in different regions and sites,[7] the ranges of values must be set according to the specific conditions of each case study, which means that there are different scenarios for each region and site (Estrada-Garcia et al. 2016). Regarding the variables, the predictive model would be measured as Eq. 10, and UFF at the *i*-th zone as Eq. 11:

$Ln(F_u) = a_0 + a_1(f) + a_2(t) + a_3(f)Ln(b+1) + a_4(f)Ln(r+1) + [a_5 + a_6(f)]Ln(h) + [a_7 + a_8(f) + a_9(t)]Ln(w)$, (Eq. 10)

(Source: Estrada-Garcia et al. 2016)

$UFF = \sum_{i=1}^{n} F_u(i) TIF(i) fd(i)$, (Eq. 11)

(Source: Estrada-Garcia et al. 2016)

The major drawback of this method is that it cannot cite the three aspects of light pollution, but only measures the amount of upward emitted light from a source (Estrada-Garcia et al. 2016).

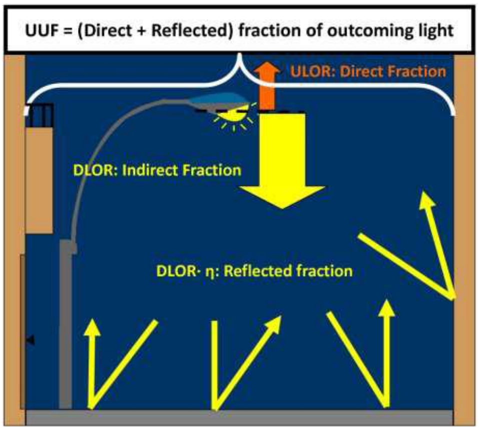

Fig 9. Computing the Upwards Emissions in a Basic Urban Scenario

Source: Estrada-Garcia et al. 2016

One way to perform this method (Estrada-Garcia et al. 2016), is to calculate the predicted fraction of up-light and the fraction of urbanized upward flux using the equations to create a 'multiple linear regression model' in two different years or multiple years. Then it is possible to compare them. Since the products of this method are overall fluxes and that of VIIRS (refer to subsection 2.2.2 to read about this instrument) data are radiances; therefore, VIIRS can be used as a complement to this method to accomplish this comparison.

3. REMOTELY SENSED IMAGERY (RS)

Remotely sensed imageries or images captured by satellites and astronauts are the main sources for urban designers to study light pollution. In fact, this method is a complementary method for other ground-based surveys to give the researcher a clearer vision of what and where the main sources of pollutions are. In a study to determine the main locations of urban light pollution (Goronczy, 2020), the images taken from NASA by satellite have been used as the main source to locate the major lighting hotspots for further studies (Fig 10a). Afterward, through measurement of ambient luminance and illuminance, the hotspots that are referred to as H (main roads) and N (sideroads) have been studied in detail (Fig. 10b, c, and d). In this section, 4 main sources of remotely sensed imageries are introduced.

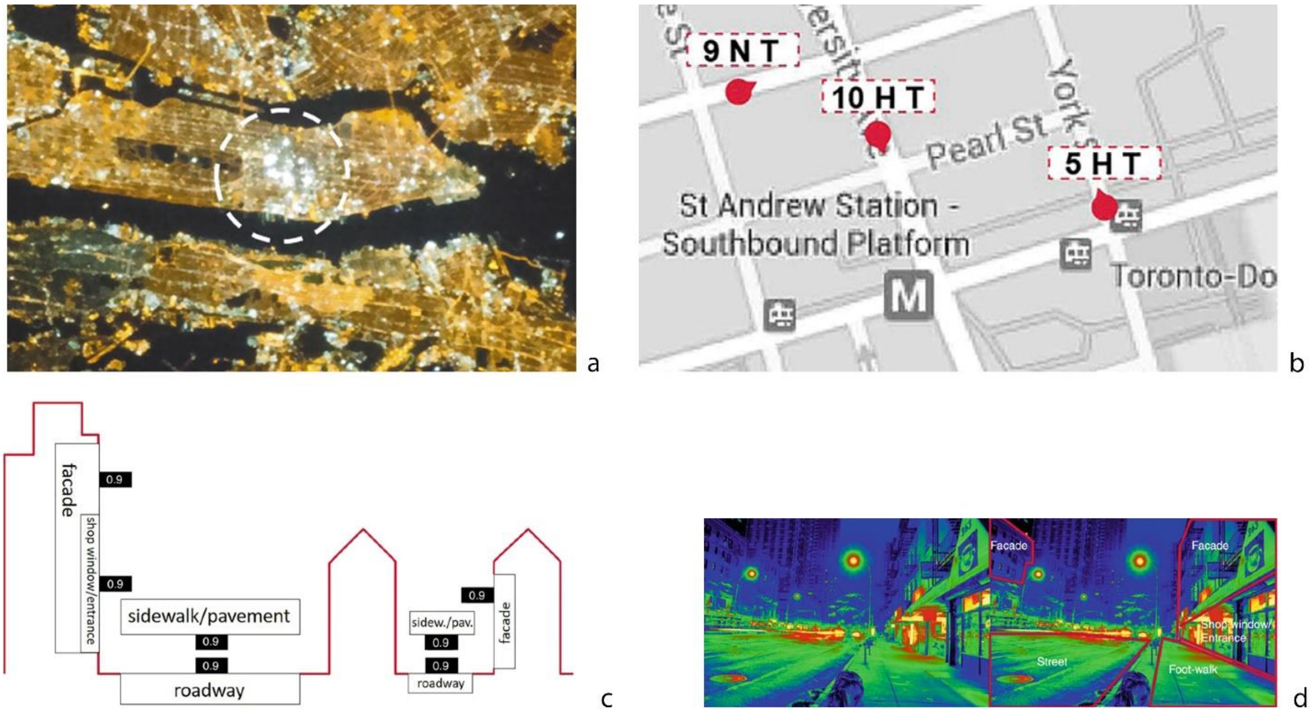

Fig 10. The Indication of Lighting Hotspots through Satellite Imageries from NASA and Google Earth (a, and b). Further Studies on the Hotspots via the Ground-based Methods (c and d)

Source: (Goronczy, 2020)

3.1. Defense Meteorological Satellite Program (DMSP) Imagery and GIS

This method is developed to indicate the quantity of up-light caused by luminaire nighttime lights in a region and evaluate the degree of light pollution in suburban areas. This method of monitoring has been employed for night-time lighting surveys and studies since 1992 (Levin, 2017) and demolished due to the advancements applied in other satellite imageries with higher resolution. Another drawback of this approach is that it is time-consuming.

The objective of estimating direct light pollution (direct visual impact of luminaires on the human eye) can be achieved by using DMSP and Digital Elevation Model (DEM) data. GIS packages present viewshed mapping, from which night luminaires can be regarded as observational points. Through these observational points from the viewshed map along with extracted points of night lights in DMSP data, the total amount of cells of lightened points that are visible can be evaluated. The output is a map illustrating the number of visible observational points (Chalkias et al. 2006).

Besides direct light pollution, there is indirect light pollution, too. It is associated with areas receiving impacts of indirect light pollution. This is referred to as observed sky glow. The illustration of the sky glow geometry is the final output of this approach. For this objective, light emissions should be assessed in flux through a light meter. The light meter demands a theodolite to be placed on it, in favor of recording the spatial shifts of emissions. These assessments lead to the achievement of the sky glow altitudes, which vary for each point of the study area. The final output, composed from these altitudes with DEM, would form the sky glow dome of the area, which is a 3-D diagram (Fig. 10) (Chalkias et al. 2006).

The relationship of light emitted upward in a city extremely depends on the population and development of the city, and it can be studied through the employment of data from DMSP (Kyba et al. 2015). On the contrary, photographs obtained by this satellite has got multiple problems explained in various references, namely ‘coarse spatial resolution, over glow, saturation in urban areas, and intra-sensor calibration problems’ (Levin et al. 2014). Alongside these problems, lack of spectral bands makes DMSP/OLS imagery impractical for studies related to the spectrum of the night sky and the nature of the lights, but it can be employed for studies on energy consumption (Sanchez de Miguel, 2015).

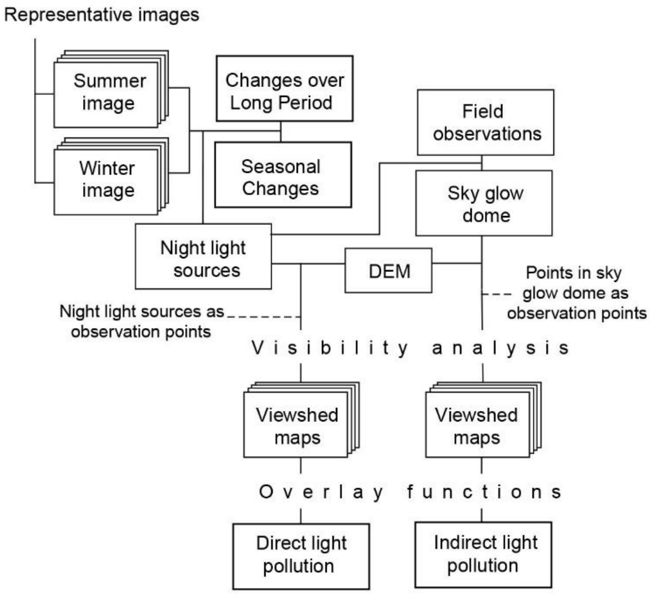

Fig 11. The Flow Chart of DMSP-DEM Methodology
Source: Chalkias et al. 2006

3.2. Visible Infrared Imaging Radiometer Suite (VIIRS) Imagery

Visible Infrared Imaging Radiometer Suite Day-Night Band (VIIRS DNB) images, which have come in vogue among experts since 2012, functions as a proper alternative for images taken by DMSP. It is because they have the privilege of a higher resolution of about 750 meters. These images have about 45-88-folds higher spatial resolution than DMSP, considering that pixel size contingents upon the latitude from which the VIIRS is flown (VIIRS is mounted on the Suomi NPP satellite) (Kyba et al. 2015). Currently, http://ngdc.noaa.gov/eog/ download.html contains cloud-free composite images.

Atmosphere airglow would influence the observations from VIIRS DNB; therefore, the sum of light (SOL) values (another variable that effects observation is the various cityscapes) would be different in various airglows over different regions (Kyba et al. 2015). In addition, different spectra of lights would produce different DNB values even if their lumen output is identical (Kyba et al. 2015). Kyba et al. (2015) have shown that the type of construction producing brightness in the sky (identified in the DNB data) can be explored and indicated using the Google Earth program. DNB is a good data source for socioeconomic studies due to lack of saturation in it, as well as for exploring the efficiency of a city agenda and planning in decreasing light pollution (Kyba et al. 2015).

The disability in detecting blue spectrum in DNB data which wrongly shows a decrease in light pollution (Flachi et al, 2016) is a defect that can be rectified by applying color information from ISS photographs to individual pixels in the DNB radiances, and afterward, it is possible to create spectral radiances of DNB radiances and thus to model sky glow (Kyba et al. 2015).

Falchi, et al. (2016) recently have developed an atlas of artificial light (Fig. 11) filtered from temporary lights and problematic conditions (mist, snow cover, etc.) through VIIRS DNB.

Levin (2017) has shown that seasonal changes in land cover properties can be detected by VIIRS DNB data. Using TerrSet geospatial monitoring and modeling software, various MODIS satellite information of variables such as snow cover, albedo, and NDVI data used to interpret seasonal and temporal changes in lighting can be manipulated in the case of interpolating missing data, etc.

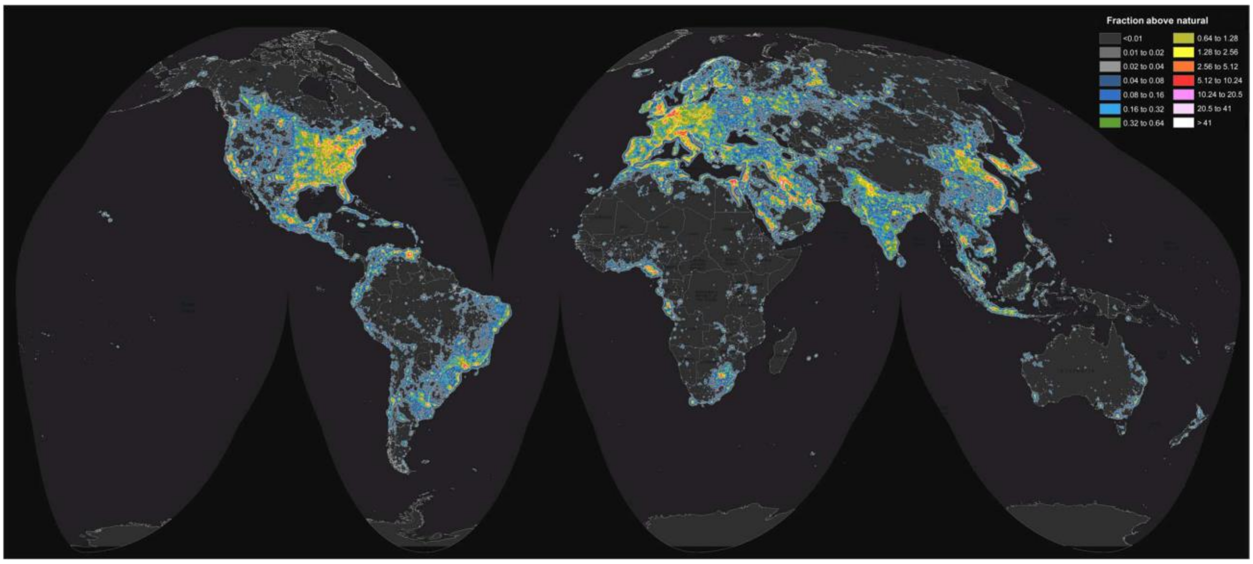

Fig 12. World Map of Artificial Sky Brightness, Source: Flachi et al, 2016

3.3. International Space Station (ISS) Photographs of Night-time

Astronaut photographs that are taken from ISS are getting the benefit of a newly installed NightPod instrument since 2012 (Gaskill, 2014). They are accessible at the NASA site as 'Atlas of astronaut photos of Earth at night' (http://www.citiesatnight.org/). This source of images of the earth at night can be tasked as a reference for researchers who work on light pollution of a specific city or region since all photos are being geotagged (Kyba et al. 2015). When utilizing these photographs and all other images taken by satellites, users should be aware of the blocking attribute of tall buildings and flora covers, since beamed light from sources covered by these elements would horizontally contribute to the sky glow (Kyba et al. 2015). The minimum resolution required for identifying light sources is 10 meters. ISS photographs benefitting from ESA's NightPod capture RBG images at this resolution, but with the imposed restriction of its geostationary orbit (latitudes less than 51.6° from the equator) (Kyba et al. 2015). Since images taken by astronauts are recorded in the RAW format, they are suitable for photometric analysis (Sanchez de Miguel, 2015).

3.4. Earth Remote Observation Satellite (EROS) Imagery

A possibility for mapping night-time imagery with high resolution has been offered by the EROS-B satellite. Researchers and users can employ this remote sensing instrument everywhere at any time, a privilege which is not available in some RS imageries like that taken from the International Space Station (ISS) (Levin et al. 2014). Furthermore, by getting benefits from a high spatial resolution (70 cm) (EROS-B, 2006), EROS-B has even higher spatial resolution than VIIRS imagery. In addition, EROS-C which has been launched in 2016 has a higher spatial resolution of 50 cm. The imagery by this method can be provided as digital number (DN) values which is feasible to be converted from the RAW format by a specialized image converter. Lit areas in the image can be described referencing to the desired threshold value which varies depending on different situations and conditions (Levin et al, 2014). Complementary data to the EROS imagery to get information on spatial patterns of night-time include road and arterial road centerlines, land use, foliage projective cover, demographic attributes (population size, dwelling structure type), and a list of the attraction travelers recommended (if it exists) (Levin et al, 2014).

Compared to other remote sensing imageries, this satellite can be used for surveying the sources of light as in (Levin et al, 2014); but as a drawback, access to data obtained by this satellite is rather expensive and has been limited (Sanchez de Miguel, 2015).

4. AERIAL SURVEY

Although the terrestrial survey of light pollution is the most accurate method to indicate light sources and count them, it is arduous and would take time. Among terrestrial and satellite surveys of light pollution, there is a practical method from which defections of the two previously explained survey methods could be eliminated. Night-time imagery through an airborne equipped by a Finger Lake Instrumentation (FLI) camera and an INS/GPS system to save information on the position and orientation of the camera which is installed below the plane, would bridge terrestrial and remote sensing methods (Kuechly et al. 2012). Onboard hyperspectral cameras which are commonly used in aerial daytime surveys are not capable of the measurement of streetlights. For this purpose, a multispectral camera is required (Sanchez de Miguel, 2015). Below, the process of acquiring an aerial image of a city at night is depicted.

Due to the capability of aerial images for recording RGB images directly with noticeably higher resolution than any other photographs captured by satellites (Fig. 13), the airborne survey is an appropriate alternative for remote sensing imagery. In investigations such as "epidemiological studies, studies of energy and socio-economic parameters that rely on time series or comparisons between different regions" (Kyba et al. 2015), and other similar studies, this method is highly recommended.

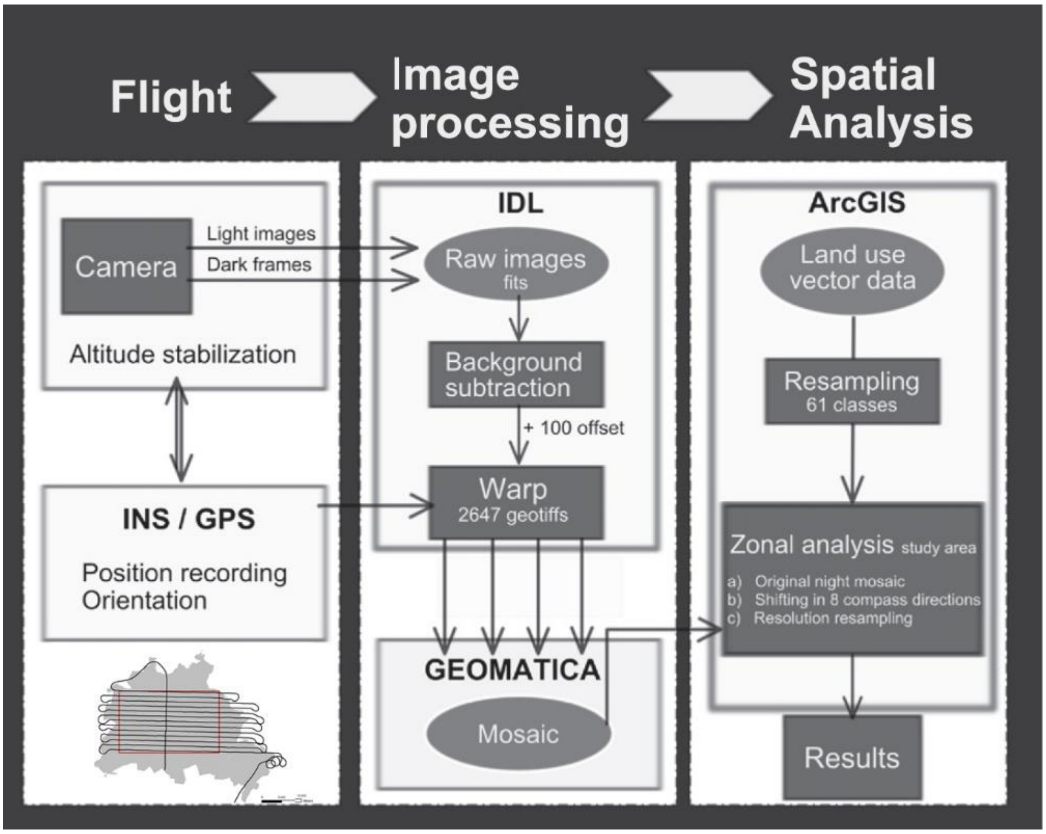

Fig 13. The Process of an Aerial Survey of the City at Night; The Pattern of Flying in a Case Study (the bottom-left corner of the figure)

Source: Kuechly et al. 2012

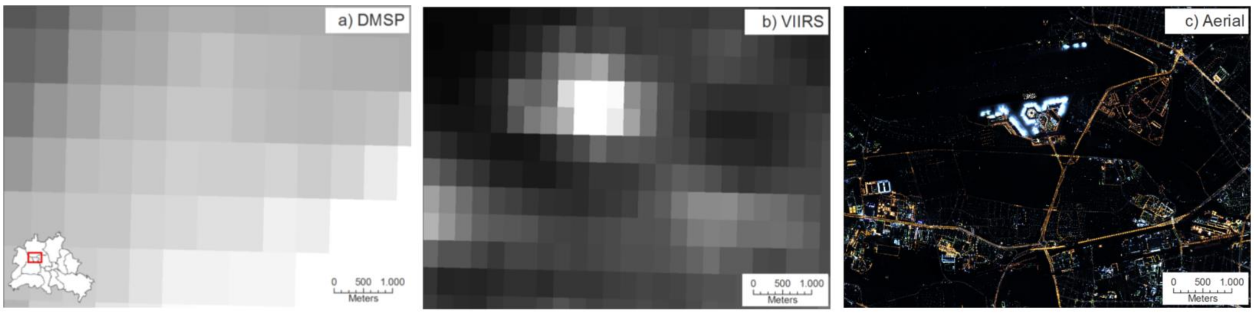

Fig 14. A Comparison between Images Taken by DMSP (a), VIIRS (b), and an Airborne (c)

Source: Kyba et al. 2015

5. CITY MODELING

City modeling is a method of light pollution identification in which indicators such as population density (Cinzano et al. 2001), economic activity (Gallaway et al. 2010), built density and urban land-use (Hale et al. 2013), road and arterial road centerlines, foliage projective cover, as well as the list of the attraction sites recommended by travelers (Levin et al. 2014) are employed to simulate light pollution. In other words, this method uses two or more techniques of the above-mentioned methods according to the need. In their survey to model a city's artificial lighting, Hale et al. (2013) utilized some sources and devices to create the city model of sky glow and to interpret it. These sources and devices were a raster layer and a point layer (representing surface illuminance and location, and the type of single luminaires, respectively) derived from processed aerial RGB images, a 'greyscale raster' generated by a spectrometer survey to consider ground incident illuminance, National Land Use Database (NLUD) zones, and Ordnance Survey MasterMap (OSMM) parcels. Furthermore, for measuring lighting at cities, they have recommended using 'land-use data' at fine scales, and 'built density data' at coarse scales (Hale et al. 2013). According to a study on indicating different economic activities (EAs) (Rybnikova and Portnov, 2017), another way to model a city is based on the emission properties of EAs' artificial illumination identification through analysis of variance (ANOVA) tests, because of the spectral and intensity of light with a certain activity emits.

Inferred from various references, to model a city precisely, the modeler should employ all the above-mentioned approaches including ground-based, aerial, and remote sensing methods according to the requirements and conditions of a specific case study. ArcGIS software tools (Rybnikova and Portnov, 2017) are widely used in city modeling, to calculate, superimpose, assign, and match different data.

6. DISCUSSION

In the previous sections, various methods and techniques of light pollution indication were extracted, reviewed, and studied. Here the most cited and practical methods which have been introduced in this article are categorized (Table 3). The represented classification would categorize and compare the techniques in terms of utilized resources and means, accuracy, the type of methodology, factor(s) of light pollution, and eventually the most related studies of each method. It is to say that each one of these methods has its own pros and cons; therefore, the user must consider the appropriate methodology (or methodologies) for their study and practice in accordance with their economic resource and requirement.

Overall, inferred from the table, OSP can be developed and utilized by architects for controlling the sustainability of their design. It can also be used by urban lighting designers to evaluate the design of luminaires or to assess their sustainability regarding the environment. Another method that can assess this pollution with affordable and handy equipment is the measurement of ambient illuminance intensity via DSLR cameras and programming software. In addition, this method could be used both for city scales and urban contexts. Mixed with obtained imageries from satellites that are available for public or experts' use, these two methods could be highly effective for urban contexts and light pollution in a city scale. For getting more precise results for the assessment of light pollution in a city, aerial survey is the most accurate and reliable way of study. For getting a better result in any urban case study, authors recommend using a mixture of these methods. For example, while direct observation might yield a low accuracy, it does not need any specific instrument to assess urban light pollution. In other words, any observer just by looking at the urban sky with good eyesight and knowledge on determining the quantity and quality of the observable stars could determine a sky as whether it is considered as a rural, suburban, or urban sky. Another issue that a researcher should be aware of is that if they decide to use terrestrial instruments to assess the quality of the sky, they should certainly use a mixture of the methods. For example, EF, the Experimental Device of Sky Glow Description, ILLUMINA, and Experimental Measurement of Sky Quality are used for the purpose of assessing sky glow. However, Measurement of Ambient Illuminance Intensity would be considered as the complementary method for them.

Table 3. Methods and Techniques of Urban Light Pollution Detection (Source: Authors)

No.	Technique	Utilized resource/s	Means	Accuracy	Type	Determined factor/s	Most related studies
1	Direct observation	- Human observer - Quantity and quality of observable stars	- Human eye	Low	Terrestrial	Sky glow; Trespass; Glare	Astronomical and urban studies
2	Experimental measurement of sky quality	- Special sensor	-SQM	High	Terrestrial	Sky glow	Urban Pollution and local studies
3	Measurement of ambient illuminance intensity	- Spatial lighting standards - Special sensors	- Lux meter - Luminance meter - Digital camera	High	Terrestrial	Trespass; Glare	Urban and Pollution studies
4	The experimental device of sky glow description	- Photograph - Software calculations	- DSLR camera - Photometric sensor - DCLUM software	High	Terrestrial	Sky glow	Light pollution mapping and related urban & regional studies
5	EF	- Night-sky photographs - Analytical function of light emissions - Garstang's emission function - Mathematic formulas and software calculations	- DSLR camera - Portable computer - Python software	High	Terrestrial	Sky glow	Light pollution mapping over a city and related urban studies
6	ILLUMINA	- 3D gridded model of the atmosphere - AOD of the sky - Mathematic formulas	- SAND spectrophotometer	High	Terrestrial; Virtual	Sky glow	Sky brightness studies in the city contexts
7	OSP	- Virtual calculator box - Precise data of city lighting	- Photopic function - Lighting calculation software	High	Terrestrial; Virtual	Sky glow; Trespass; Glare	Design studies of facilities and luminaires' function
8	Optimal Linear Regression Function	- Software calculations and mathematic formulas	- Software package CALCULUX	High	Terrestrial	-	Pollution studies of single lighting installations
9	DMSP remote sensing	- Nighttime satellite photo	- Meteorological and photographer satellite	Low	Celestial	Sky glow	Regional and demographic studies
10	VIIRS remote sensing	- DNB data	- Meteorological and photographer satellite	Medium	Celestial	Sky glow	Global, Regional, and local studies
11	ISS imagery	- Nighttime celestial photo	- Space station	High	Celestial	Sky glow	National, and local Studies and studies related to light spectra and lighting levels

No.	Technique	Utilized resource/s	Means	Accuracy	Type	Determined factor/s	Most related studies
12	EROS remote sensing	- Nighttime satellite photograph	- Meteorological and photographer satellite	High	Celestial	Sky glow	Local and urban planning and studies and studies of light sources
13	Aerial survey	- Aerial photograph	- Airborne - INS/GPS system - FLI camera - Geomatica software - ArcGIS software -IDL software	High	Aerial	Sky glow; Trespass	Urban and local studies, and determination of lighting levels
14	City modeling	- Population indicators - Economic indicators - Fabric indicators - Nighttime satellite photograph - Mathematic and software calculations - MODIS/Terra data	- Meteorological and photographer satellite - Ground-based instruments - Specific software (ArcGIS, etc.)	Very High	Terrestrial; Celestial; Aerial; Virtual	Sky glow; Trespass	Urban studies and studies related to light pollution

7. CONCLUSION

Through an overview of the concept of urban light pollution and its methods of detection, a relatively wide scope of this issue along with the problems of cities is demonstrated. Urban light pollution, as mentioned in previous contents, has irreparable impacts on ecosystems and causes negative effects on various aspects of human and other creatures' lives. In this paper, by reviewing different types of light pollution indication methods and summing them up in 14 different categories including direct observation, experimental measurement of sky quality, measurement of ambient illuminance intensity, the experimental device of sky glow description, EF, ILLUMINA, OSP, Optimal Linear Regression Function, DMSP remote sensing, VIIRS remote sensing, ISS imagery, EROS remote sensing, Aerial survey, and city modeling, the similarities and differences, as well as the advantages and disadvantages of these techniques were discussed. To assess the light pollution of a city which is the main part of the analysis stage of creating an urban lighting master plan, a mixture of terrestrial, virtual, aerial, and celestial methods should be considered to model a city. The best way to study the luminaires in a certain facility or a road seems to be the OSP method along with the use of other devices introduced earlier. To have a precise outcome of the terrestrial assessment of sky glow, the methods of EF, the Experimental Device of Sky Glow Description, ILLUMINA, and Experimental Measurement of Sky Quality should be used altogether. It seems that for the measurement of glare, there are just two methods that are Measurement of Ambient Illuminance Intensity, and Direct Observation.

Finally, this research aimed to introduce and categorize methods and approaches allocated to urban light pollution issues, provide base information for urbanist, lighting, and architectural researchers. It can be utilized for the next research and practices in this field. Eventually, it is to say that regarding the advancements made in satellites and photography technologies as well as specialized software products, the invention of newer and more efficient methods can be expected.

NOTES

1- To have a conclusive evaluation of sky brightness, subtracting effects associated with natural sources, and SQM spectral response, refer to the tables and equations located in the paper by Sanchez de Miguel et al. (2014).

2- The assessment equation for obtaining F is represented in Lamphar and Kocifaj (2016).

3- For example, in a survey through an aircraft flying low, the recorded signals of emitted lights are radiated from various angles. Furthermore, the emitted signals would be distorted in different ways for the sake of atmospheric extinction at curved directions; or in a satellite nighttime image, controlling EF is only available at zenith angles and obtained data in this method would fluctuate (Lamphar and Kocifaj, 2016).

4- The whole calculation process is available at (Kocifaj, 2017).

5- I_1 is a direct scattered intensity; I_2 is a beam intensity firstly scattered by cell 'm'; I_{r1} is a beam intensity which has been reflected from a pixel of the surface; and finally, I_{r2} is a beam intensity first reflected from a pixel and secondly scattered by another cell and eventually has crossed the intended voxel (Aube, 2015).

6- The average percentage of the street filled by buildings.

7- The coefficients and further equations such as calculating the value of F_u are listed and available at (Estrada-Garcia et al. 2016)

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