Problem Chosen	2022 MCM/ICM Summary Sheet	Team Control Number
E		2313910

Starry Starry Night

The fascination of the night and stars in human civilization is a story as old as time itself, yet with the incredible speeds of technological developments and advancements, we see less and less of the dark sky that used to intrigue us so much. We seem to forget how important that darkness is to us and to the other entities we share the earth with, as the once dark night slowly resembles daytime and we can no longer differentiate between the two. Light pollution, the unnecessary abuse of artificial light, has become a part of our day to day lives that not many are even aware of its effects. As part of the Illumination Control Mission(ICM), we were challenged to develop a broad standard to measure the risk of light pollution and its effects, and come up with strategies to mitigate the damages, as well as spread awareness about it so that the situation doesn't worsen. To meet that goal, we break down the risk measurement into two models; **Model I: Local Risk Evaluation** and **Model II: External Risk Evaluation**, with one measuring the risk when observing from within a certain land type, and the other measuring the effect nearby strong light sources have on the observer. We then get the total risk value by combining the two.

For Model I, We only prioritize internal causes so this report examines the causes that are related to the light pollution level at every terrain type within itself. We compute weights in terms of how much these causes affect the overall pollution level using the Entropy Weight Method(EWM) to account for inconsistencies among different data dimensionalities. Since this is a risk evaluation, we also calculated a likelihood matrix that indicates the probability of a recurring effect to manifest itself in that particular terrain.

For Model II, We consider the network effect that other nearby urban areas or sources of large amounts of light production have on the terrain the observer is from by using a physics informed model. We consider the particles in the air that reflect light, the different wavelengths emitted from the source, the altitude of the observer, the surface type(in other words, coastal city vs. inland, asphalt vs. snow etc). We also take a population threshold into account, that is, when a city reaches a certain population, the light pollution risk will be penalized disproportionately to reflect the vulnerability of the city's projected risk level.

We then incorporate both models and develop a 3 strategies proposal(Favorable-Recommended-Mandatory plan) that varies by difficulty of implementation and personal to government assistance needed actions. We then evaluate the effectiveness of each at urban and protected lands and find that the favorable strategies are more effective in less dense areas, while mandatory strategies have more impact on urban environments, confirming our intuition. The strength of our model lies in the fact that it is easily combinable with other existing models from professional studies and that it is much more comprehensive than solely relying on the satellite images to determine light pollution risk. We also address our model's limitations due

to us only utilizing current data, thus the model might not be as accurate as time goes on, and ways to improve such limitations. We hope that with the information we provide, more people can be informed on the effects of light pollution and that we might one day see the sky Van Gogh depicted in his work once more no matter where we are.

Keywords: Physics-informed Simulation, Constraint Optimization, Entropy Weight Method, Network Effect, Promoting Sustainability Awareness, Risk Quantification

1 Introduction

1.1 Problem Background

With the rapid advancements in technology, humans seemed to have left the dark ages behind, but is it really a good thing? The modern society now faces light pollution, a new form of pollution beyond the traditional definitions of conventional pollution. It is categorized by the excess use of light that it causes harm to both humans and the ecosphere that we share with other organisms. Though the topic has been decently well studied and explored, the general public is not yet educated on it relatively. Yet the effects are jarring. Past scientific research has shown that the light pollution in bigger cities, many residents report insomnia or mental health issues; Since light has the capability to reach far beyond the perimeters of the source, it also affects animals and plants near and far alike. Even though progress has been made recently, a better way to quantify the impact of light pollution is needed beyond simply analyzing the satellite images and sulking in pessimistic thoughts.

Figure 1: a comparison of a city with and without light pollution[1]

Challenged by the ICM, we built a model to evaluate the risk level of light pollution taking different types of land into account, came up with possible strategies to mitigate the effects of light pollution, and demonstrated their effectiveness with our metrics.

1.2 Restatement of the Problem

Considering the background information and tasks identified in the problem statement, we need to solve the following problems:

- Develop a metric to quantify the **Risk Level** of light pollution and apply it to 4 different location types: Urban, Suburban, Rural, and Protected Lands.
- Introduce 3 intervention strategies to address light pollution in general and how the strategies are manifested in terms of potential impact.

- ❖ By choosing 2 location types, demonstrate the effectiveness of each strategy by evaluating the risk levels after the strategies have been implemented.
- ❖ Produce a flyer for one location type and advocate the most effective intervention strategy catered to that specific location.

1.3 Our Work

The question asks us to examine the overall light pollution and establish a broad metric to measure risk level at any given location, as well as deriving possible policy changes to prioritize both human and non-human effects of light pollution on a large scale. Our work mainly includes the following:

- ★ Model I: Local Impact Evaluation Model: We establish a cause and decision based model and use the Entropy Weight Method(EWM) to determine the human and non-human risk index on a local basis for each location type.
- ★ Model II: External Impact Evaluation Model: We establish a physics informed model to calculate how much light from a nearby city or land will affect the light pollution at the location of interest.
- ★ We then combine these two models and utilize them by investigating how much risk is at one of the four land types mentioned in the question statement as well as making model informed policies.

In summary, our entire modeling process can be shown as follows:

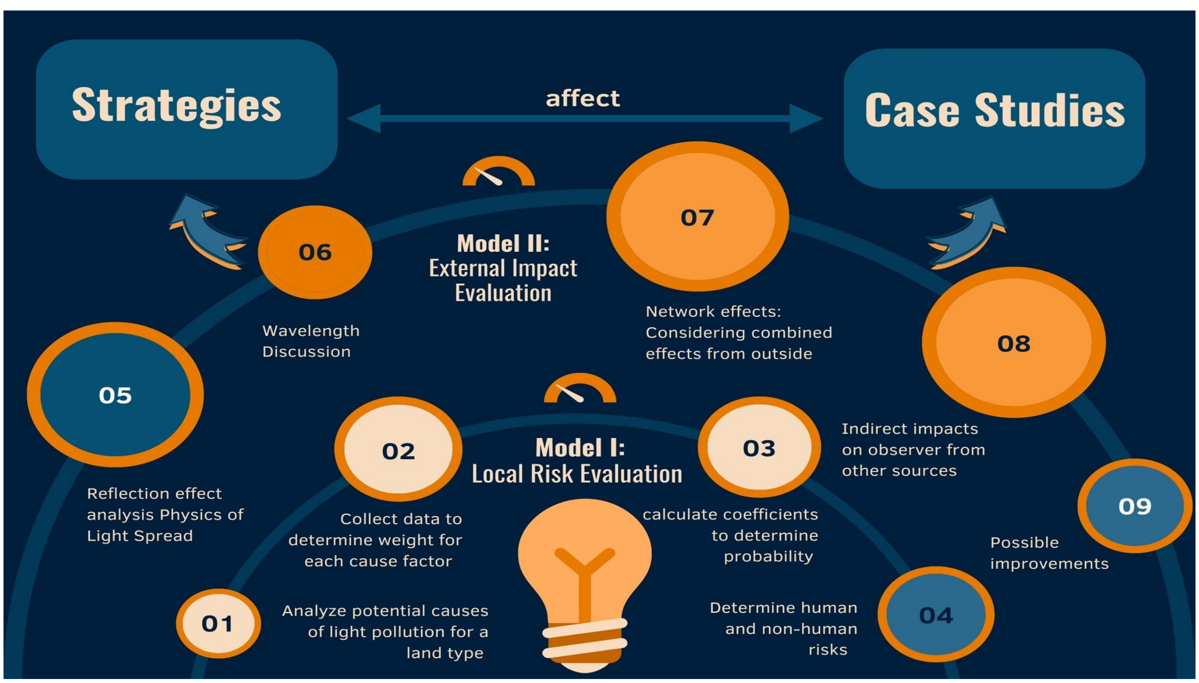

Figure 2: Model Overview

Since in order to evaluate a location's risk level to light pollution, we need to consider both the local effect caused by exposure to light from within the source and the effect other nearby light sources have on an entity, thus we split our analysis into two parts, with one calculating a local impact and the other an external impact that analyzes the network effect caused by others. Both impacts will then be broken down into effects on marine creatures, effects on land animals(which are both non-human impacts), effects on human health, and effects on quality of astronomical research and observation. We would then consider strategies to implement and use case studies to verify the effectiveness, and study what limitations can be improved.

2 Assumptions and Justifications

To simplify the problem, we make the following basic assumptions, each of which is properly justified. Other assumptions pertaining to the specific models will be discussed later in detail.

- We assume that the behaviors from human to human and from species to species are relatively similar, and the changes in behaviors we analyze are caused only due to light pollution.
  - **Justification:** Although each human behaves differently and the behaviors of animal species vary, it would require more data and some are hard to quantify. Additionally, there have been studies that examine the results of light pollution effects, therefore we assume it is a one to one relationship.
- We assume that the terrain the major light sources emit from are relatively flat, and the effect of such light sources are the same no matter where the observer is standing or which direction one faces.
  - **Justification:** Due to the physics-based nature of our model, the maximum effect that a nearby city can have on a point of interest is already calculated, and that is the index that offers us the most insight on the risk of light pollution.
- We assume that 80% of the light emitted from a city comes from its center, and gradually decreases as one moves away from the center.
  - **Justification:** for the ease of calculation, we will use the Pareto Principle to avoid building another model for light emission since we are considering the effect of light pollution in the city as a whole for external effects.
- We assume that light pollution is only caused by a fixed set of factors.
  - **Justification:** Some factors of light pollution are harder to quantify, and we could not obtain data for some, so we made some reasonable combinations and measured some from a proportional standpoint.

3 Introduction

The risk level of light pollution at a point can be broken down into the sum of likelihood of an effect to take place times the size of said effect over all the possible effects. As explained in the diagram below, every possible impact is affected by a set of different characteristics of light.

$$risk = \sum_{e_i \in E} Probability\left(e_i\right) \cdot Impact\left(e_i\right)$$

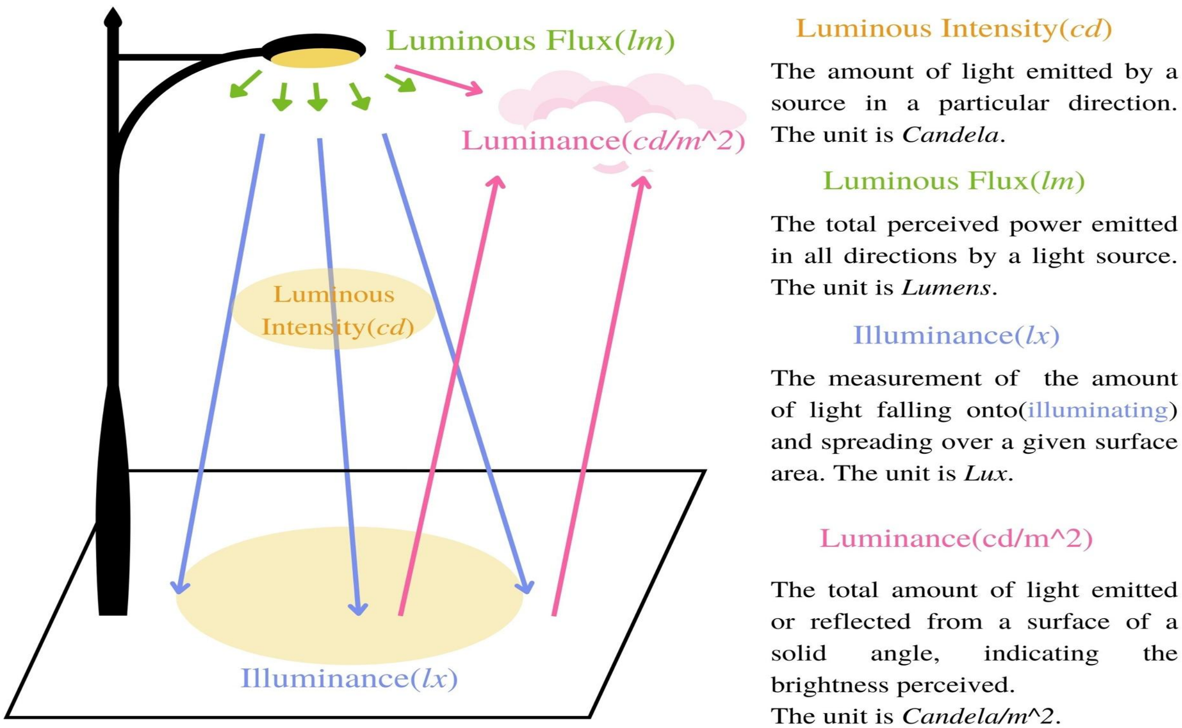

Figure 3: Measuring light intensity

Among all the possible $e_i \in E$, we want to focus on 4 particular effects of light pollution because they each represent a class of effects of specific nature. We classify them as such with the table below:

Effects	Likelihood of happening (temporal & spatial)	Affected by which characteristics of light	More concerning in the center of the city or in the surroundings of a city?
e_1: human health	always, everywhere	Luminous flux	Center
e_2: astronomical observatories	sometimes, only for somewhere	Luminance of wavelength(nm) of	Surroundings

		[500,620], in certain directions	
e_3: bird migrations	Rare, only during particular times of the year, only for places along the migration path	Luminance of wavelength(nm) of [450, 500]	Center and surroundings
e_4: algaes	always, only in the water	Illuminance of wavelength(nm) of [640, 700]	Surroundings

Table 1: Breaking down the effects of light pollution

Hence, it is easy to see that the challenge of quantifying the risks is that:

- ➔ The "size" of an effect is very hard to measure.
    - ◆ Though the satellite data provides a birds-eye view of the brightness of the ground(luminous intensity), mapping the initial intensity and the causes to the specific effects is hard.
- ➔ "Probability" of an effect taking place is hard to measure.
    - ◆ The likelihood of an effect could only be concluded from city centers that have more comprehensive census and mature benchmarks. In the less developed or the rural areas, the probability of the same effect is hard to quantify.
    - ◆ When the event is rare, for example, bird collisions follow from the tail distribution of a parametric distribution. For the data we have, we could reliably use probability only when we refer to the expectation of a recurring event.

Thus, based on what we can reasonably deduce about the "probability" and "size" terms, we decouple the modeling of overall risk into modeling the risks due to external causes, and the risks due to internal causes, hence an external risk index and a local risk index.

3.1 Defining "risk"

So far we used "risk" as an abstract concept; here, we will give a concrete quantification of risk. Using the raw number of light pollution data from the satellite can be misleading because many factors of a location should also be inputs for determining the risk.

Instead, we take up the bottoms-up approach to study all the possible causes and their respective amounts at that location, and draw probabilistic causal mappings to derive the corresponding effects, the sum of which we define as the **internal risk** of the location. But this measurement has the potential to be accurate only when we have (close to) complete data at hand - which is the case for the urban land type.

For the other three land types, we simplify the internal risk because of the missing data and the absence of the network effect that features the urban land type. As it is also often the case that light pollution is a result of external factors some place away from the location of interest, we define **external risk** of that location to be the abundance of *harmful* light phenomena attributable to glowing cities nearby. The emphasis here is what we mean by *harmful* - the light of specific wavelength, color tone, or other characteristics that directly affect the humans, plants, or animals that we care about in the study.

To sum up, **internal risk** is the result of appropriate mappings of cause factors and the availability of data makes such mapping statistically sound. On the other hand, **external risk** is the result of filtering light pollution at a distance to its *harmful* proportion. This time, the selective subset of causes themselves serve as a direct representative of its associative risk.

4 Model 1: Internal Risk Evaluation

Firstly, to measure the local effects and risks of light pollution, we wanted our model to be a cause factors driven model, that is, we measure the risks by analyzing causes of light pollution and that different causes can lead to an array of different effects. We separately measure the effects to determine the risks to humans and non humans alike. We break down different causes in each land type, like so:

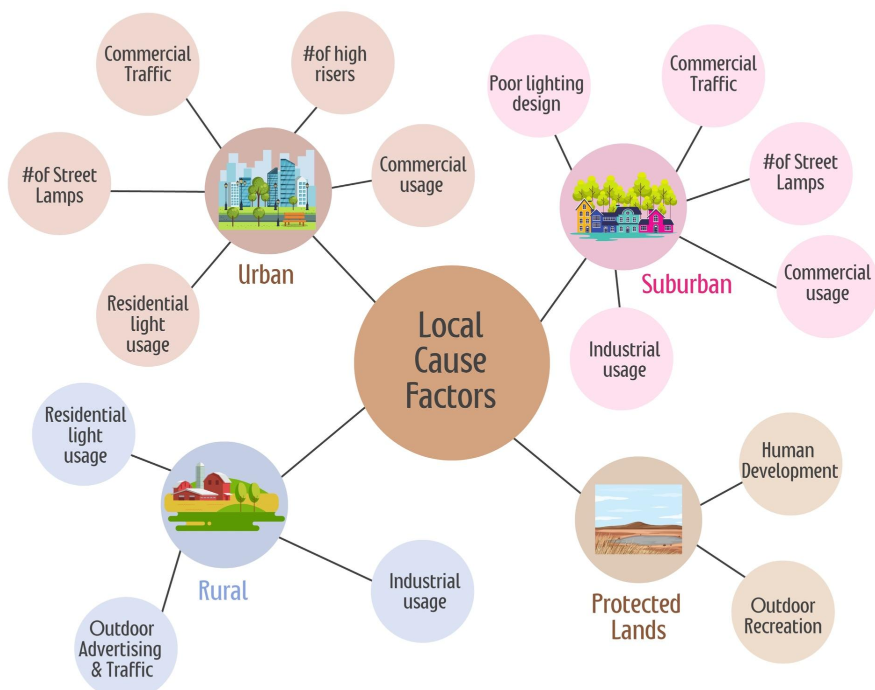

Figure 4: Breaking down the cause factors based on land type

Our model for internal risk is driven by cause factors, whose composition and amounts depend on the land type. Thus we will fix a land type, and study the associative cause factors and how they mediate, through a likelihood matrix, to the corresponding effects, like so:

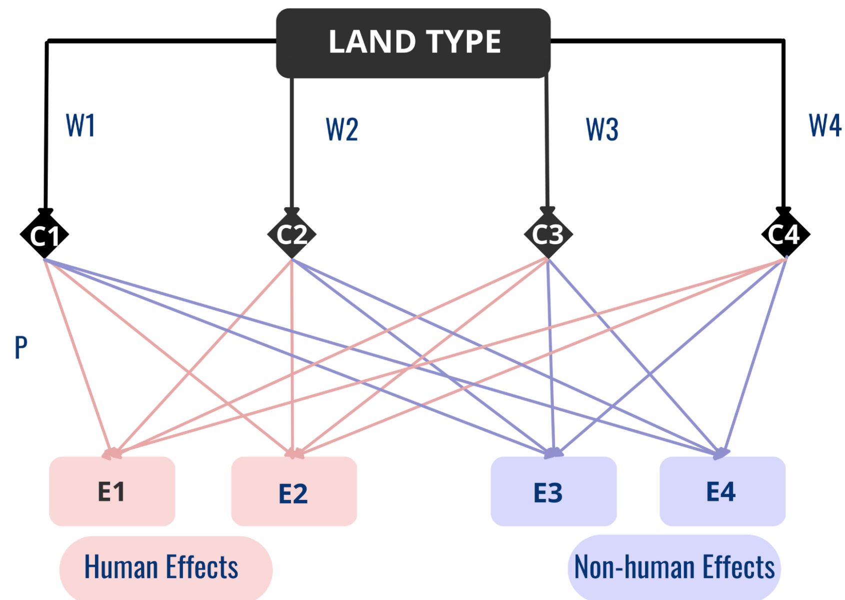

Figure 5: Our Method of mapping causes to effects

Our model is summarized with the equation below, where a * in the subscript means that this value will change when we change to another land type:

$$Internal\ risk = WCPBE$$

$$= \begin{bmatrix} w_1^* & \dots & w_m^* \end{bmatrix} \begin{bmatrix} c_1^* & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & c_m^* \end{bmatrix} \begin{bmatrix} p_{11}^* & p_{12}^* & p_{13}^* & p_{14}^* \\ \vdots & \vdots & \vdots & \vdots \\ p_{m1}^* & p_{m2}^* & p_{m3}^* & p_{m4}^* \end{bmatrix} \begin{bmatrix} b^* & 0 & 0 & 0 \\ 0 & b^* & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_4 \end{bmatrix}$$

4.1 Understanding *BE* and *C*

BE is a tuple of impacts per-unit of a single effect, scaled by a balancing factor to distinguish the priority between effects on humans(red) and that on non-humans(blue). *C* measures the abundance of cause factors within a land type. Taken closer, it represents a group of concrete census from electricity use for industrial purposes to the number of high risers. To prevent taking into consideration confounding variables, we only look at the non-overlapping cause factors that generate light by itself.

4.2 Understanding *P*

$P \in R^{m\times4}$ (where m is the number of causes when we fix a land type) is the likelihood matrix that propagates the cause factors to effects. P_{ij} shows how likely cause i brings about effect j independent of everything else. We assign values to the entries based on how strong the temporal and spatial causal links are, using the analytic hierarchy process.

We assume that each unit of cause factor, with a certain probability, induces one unit of effect. Thus fixing a unit of effect, we find its balanced unit impact and then multiply it by the linear combination of all likelihood terms responsible for that effect to take place. After that, we multiply it by the amount of causal factors, which gives us the partial internal risk due to a single cause.

4.3 Understanding *W* and estimating it with Entropy Weight Method

We have a list of *m* risk values, each attributable to one of the *m* cause factors. Now we want to determine the weights of these *m* terms when aggregating them into the comprehensive **internal risk** term. The inconsistent dimensionality among these partial risk values and assuming correlation leads us to use the entropy weight method(EWM). Let $X_1,..., X_m$ denote the m components of ***CPBE***, we then sample 10 places for each X_i to perform the min-max transformation on each X_{ij} to obtain a corresponding $y_{ij} = \frac{(x_{ij} - min(x_i))}{(max(x_i) - min(x_i))}$, $j = 1, 2,..., 10$. With the standardized values, we compute the respective proportion $q_{ij} = \frac{y_{ij}}{\sum_{j=1}^{n} y_{ij}}$ and the information entropy $e_i = - ln(10)^{-1} \sum_{j=1}^{10} q_{ij} ln(q_{ij})$ for each cause factor i. We can finally compute the weight as $w_i = \frac{1 - e_i}{10 - \sum_i e_i}$.

5 Model 2: External Risk Evaluation

5.1 Physics background

Skyglow refers to the phenomenon of night sky luminance that arises from either starlight, zodiac light, or artificial light. Light Scattering is the main mechanism by which skyglow occurs, and it can be divided into three categories, Rayleigh Scattering, Mie Debye Scattering, and Geometric Scattering, based on the ratio of the diameter of scattering particles and the wavelength of incident light. Rayleigh Scattering describes scattering by particles less than one tenth of the wavelength of the scattered wave, and the magnitude of scattering is strongly dependent on the wavelength. On the visible spectrum, violet-blue and red have the shortest and longest wavelengths, respectively, which is the primary reason for the red appearance of sunset and blue appearance of the sky. Mie Scattering, on the other hand, deals with larger particles and isn't dependent on wavelength. Scattering angles are important in both Rayleigh and Mie Scattering.

Given the scattering effects' dependence on wavelength, we first investigate the light intensity of commercially available light sources across the visible spectrum, **Figure 6** below. Given that the vast majority of light bulbs currently in use are LED, we made the assumption that the wavelength intensity distribution of white LED lightbulb is representative of that of the entire city. We further divided the visible spectrum of 400 to 700 nm into 6 groups, each with a margin of 50 nm and computed the percentile contribution of each.

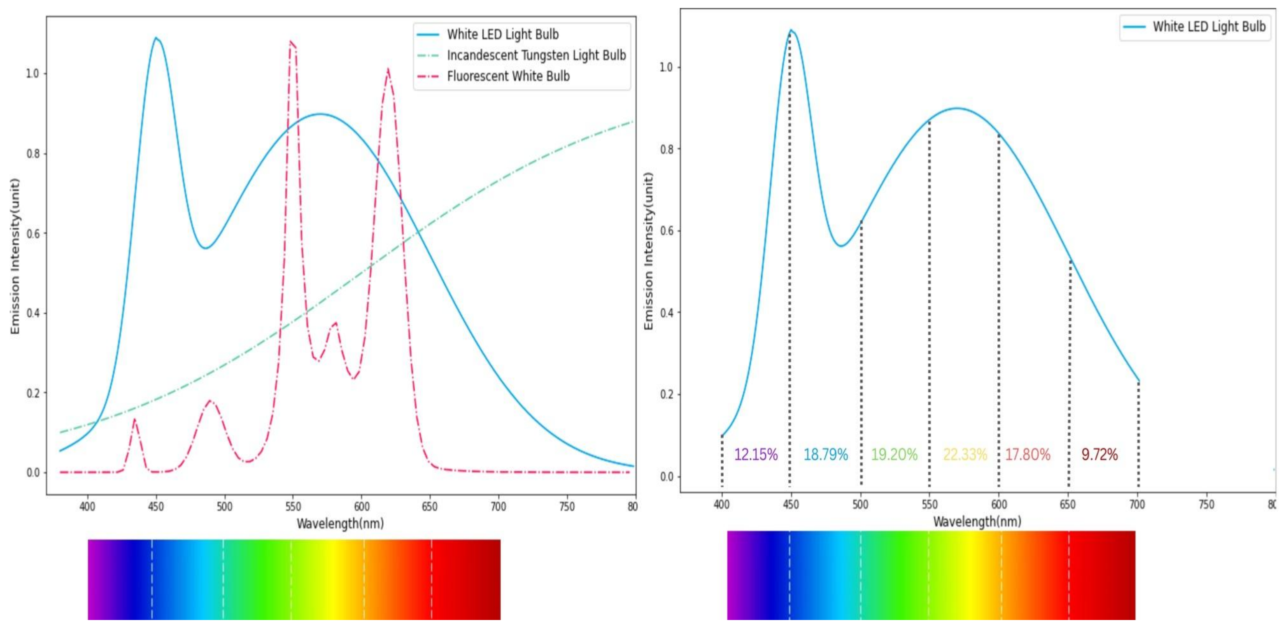

Figure 6: Radiation Intensity of Lights from the Visible Spectrum

5.2 Modeling the Artificial Light Output from Nearby Urban Cities

In our model, we desire to quantify the scattering effect of artificial light sources from a city onto surrounding areas, separated by a distance ranging from 5 km to 120 km. First, we model the city with a circle whose area equals the area of the city. The circle is further divided into two regions, an inner circle which we term the "city core", and the rest termed "city surroundings". We hypothesize that 80% of total light luminance arises from the city core with uniform distribution, while the city surrounding experiences an exponential decay of light intensity with respect to its distance from the city center (**C**), contributing to a total of 20% of light output, shown in the figure below.

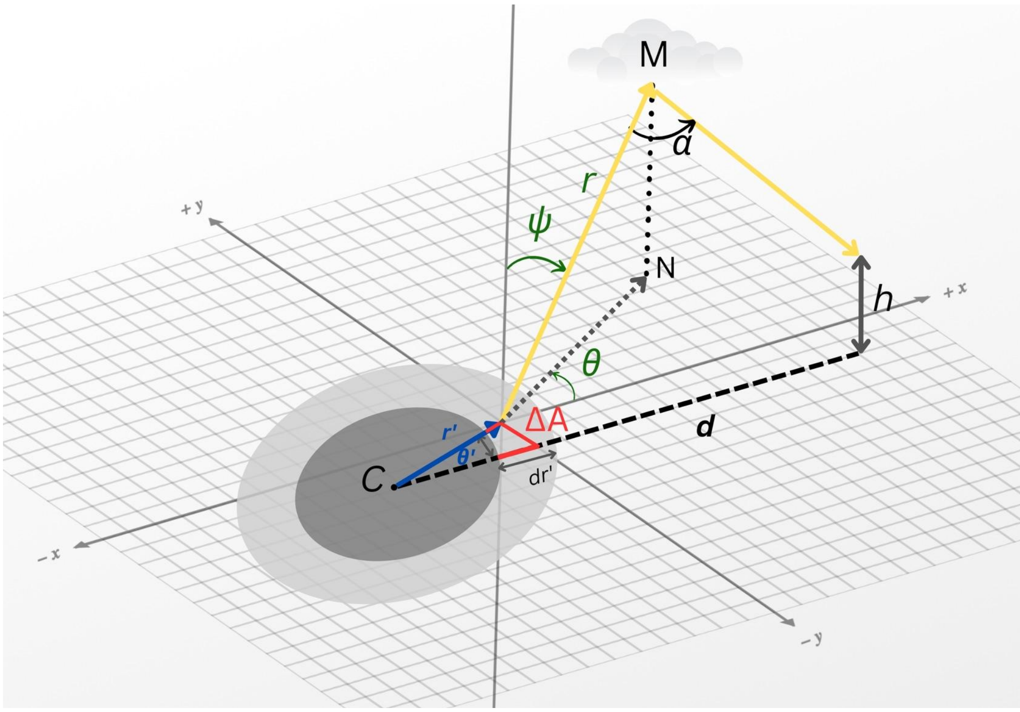

Figure 7: Schematic Representation of Light Source from City C Affecting Observer

$$\Delta L_{\lambda_i}(r',\theta') = \begin{cases} 3.2\ p_{\lambda_i}\ L & if\ r' \le \frac{1}{2}R \\ 3.2\ p_{\lambda_i}\ L\ exp(-\frac{9.48}{R}(r'-\frac{1}{2}R)) & if\ r' > \frac{1}{2}R \end{cases}$$

ΔL_{λ_i} describes light emission per unit area, (r',θ') describes the position of current light source with respect to the city center C, p_{λ_i} is the percentile contribution of wavelength group i in the radiance graph of LED white. L represents the amount of light flux based on high-resolution satellite images, and lastly, 3.2 and 9.48 are normalization factors.

5.3 Modeling Light Intensity in the Vertical Direction of Angle ψ

$$\Delta L_{\lambda_i,up}(r',\theta',r,\psi,\theta) = \Delta A L_{\lambda_i}(r',\theta')\{\frac{24}{\pi^3}P\psi^2 + 1.4(1-P)Qcos(\psi)\}$$

Based on our calculation, we came up with the equation above to show the light intensity level in the zenith direction ψ. $\Delta L_{\lambda_i,up}$ is the amount of light in wavelength group i emitted upward at angle ψ from current position, (r,ψ,θ) describe the position of the scattering particles M (O_2, N_2 molecules and aerosols) with respect to the current location. $\Delta A = (\Delta r')(r'\Delta\theta')$ is the current area.

$P \in [0,1]$ is the proportion of light directly transmitting upwards, and it depends on the design of street lamps, as shown below.

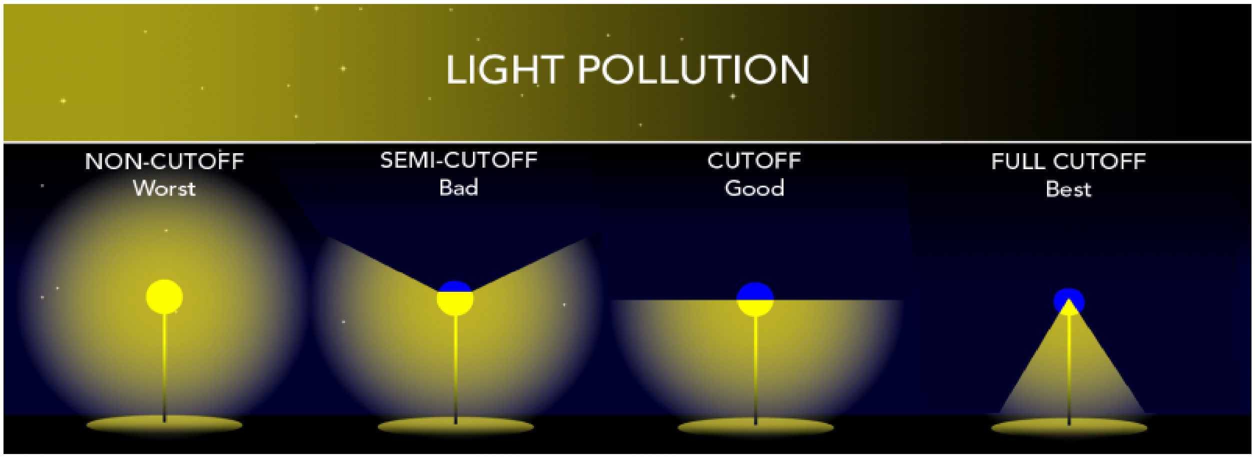

Figure 8: How different lamp designs affect amount of light vertically

Among the $(1-P)$ amount of light traveling downwards, $Q \in [0,1]$ is the proportion of light reflected back towards the sky, and it's a convex combinations of three values, $Q_{asphalt}, Q_{snow}, Q_{sea}$, based on the city's surface conditions(whether the city is coastal, and how many inches of snow the city gets).

Lastly, $\frac{24}{\pi^3}$ and 1.4 are normalization constants chosen so that the integral over the upper hemisphere would match the intensity of all light that's not absorbed by the ground. ψ^2 comes from the assumption that most street and outdoor lamps have little intensity towards the zenith direction and strong intensity towards horizontal areas. The cosine term comes from Lambert's cosine law of luminous intensity after surface reflection.

5.4 Modeling Light Scattering at an angle α onto the Observer

Suppose our observer(the region being affected) is located at a distance *d* from the city center and at a height *h* above the plane.

$$\Delta L_{\lambda_i,scatter} = \Delta L_{\lambda_i,up}\{\sigma_A N_A + \sigma_{N_2} N_{N_2} + \sigma_{O_2} N_{O_2}\}$$

$\Delta L_{\lambda_i,scatter}$ is the amount of light from the current light source that's scattered by scatter particles M onto the observer. σ_A is the scattering efficiency factor of aerosol via Mie-Debye Scattering, which, given its computational complexity, is simplified into

$$\sigma_A(r,\psi,\theta) = \sigma_A(\alpha) = \frac{K_A e^{-\alpha}(cos(\alpha) + \frac{1}{2}(3cos(\alpha)^2 + 1))}{({d_1}^2 + {d_2}^2)}$$

where K_A is a constant that depends on the cross sectional area of the aerosol molecules. α is the angle of scattering, N_A is the number of aerosol molecules per unit area, modeled by exponential regression, $N_A(r,\psi) = N_{A_0} Exp(-Altitude)$. σ_{N_2} is the scattering efficiency factor of N_2 molecules via Rayleigh scattering:

$$\sigma_{N_2}(r,\psi,\theta) = \sigma_{N_2}(\alpha) = \frac{8\pi^4 K_{N_2}(cos(\alpha)^2 + 1)}{({d_1}^2 + {d_2}^2)\lambda^4}$$

Here K_{N_2} is the constant that depends on the polarizability and cross-sectional area of the nitrogen molecule. N_{N_2} is the number of nitrogen molecules per unit volume, and it's calculated by chemical potential energy and ideal gas law. The case of oxygen follows exactly the same as nitrogen, except for the constant term K_{O_2}.

5.5 Integration Over Entire Space and City Area, Summation over all Visible Wavelengths

By performing a spherical integration over the entire space of scattering particles, we have

$$L_{\lambda_i,scatter}(r',\theta') = \int_0^{2\pi}\int_0^{\frac{\pi}{2}}\int_{500}^{\infty} \Delta L_{\lambda_i,scatter}(r',\theta',r,\psi,\theta)\; r^2 sin(\psi) dr d\psi d\theta$$

Which describes the total amount of light damage done onto the observer by light source in the current area. Another integration over (r',θ') yields

$$L_{\lambda_i,totalscatter} = \int_0^{2\pi}\int_0^{R} L_{\lambda_i,scatter}(r',\theta')r'dr'd\theta'$$

which computes the total amount of light damage within the *i*th wavelength group by the entire city onto the observer.

$$L_{totalscatter} = \sum_{i=1}^{i=6} L_{\lambda_i,totalscatter}$$

sums up the entire amount of light damage over all wavelengths from the visible spectrum onto the observer.

So, our model of external risk, from a high perspective, takes the form:

$$\sum_{\lambda_i}\int_{r',\theta'}\int_{r,\psi,\theta} L_{\lambda_i,scattering}(r',\theta',r,\psi,\theta)$$

5.6 Estimation of the Model Parameters

Our model parameters were chosen based on training with composite datasets of i) 80 data points from high-resolution satellite images from citizen-scientist program (NOAO/NSF Nighttime Sky Brightness Monitoring Program) and ii) 6 data points from las cumbres observatory global telescope network.

Strongest weights were assigned to telescope measurements from astronomical observations, and measurements from hand-held devices were also preferred over satellite images. We define the loss function to be

$$\underset{parameters}{argmin} \sum_{d\in Dataset} \beta_d\{(L_{P,d} - L_{O,d})/min(L_{P,d}, L_{O,d})\}^2$$

$$\beta_d = \begin{cases} 0.1 & if\ d \in \text{Satellite Data Set} \\ 0.2 & if\ d \in \text{Light Metric Data Set} \\ 0.6 & if\ d \in \text{Telescope Data Set} \end{cases}$$

$L_{P,d}, L_{O,d}$ represents the predicted and observed total scattering, respectively.

We choose least square percentage regression because previous research has shown that when the relative error is normally distributed, least squares percentage regression provides maximum likelihood estimates.

5.7 Determination of K_A, K_{N_2}, and K_{O_2}

Given that no closed form solution to the Mie Scattering exists, and our model assumes a simplified formula of σ_A, K_A must both match the amount of impact attributed to aerosols and satisfy the units from dimensional analysis. Since there's only data on average Reyleggh cross-sections of air molecules instead of those specific to nitrogen and oxygen, and the single/double ionization state can significantly impact their cross sections, we need to fit the K_{N_2}, and K_{O_2} parameter as well. Since we know that the loss function described above is convex with respect to these parameters, and the derivative is easily computable, we performed a constrained optimization with the Nelder-Mead method. Our constants were evaluated to be K_A $=3.84 * 10^{-7}$,K_{N_2}=$1.69 * 10^{-18}$,K_{O_2}=$1.54 * 10^{-18}$.

K_A took a value higher than expected and contributes to approximately 30.4% of the total amount of total light scattering at sea level, which is around 20% higher than the previously published 25% . Further, our values of K_{N_2}, and K_{O_2} were at the ratio of 1.1:1, which is in agreement with the fact that nitrogen molecules are slightly larger than oxygen molecules, with their gas viscosity at a ratio of approximately 1.07.

6 Combining the two models

We can combine the internal risk model and the external risk model in a convex fashion as $Overall\,risk = \theta \cdot Internal\,risk + (1 - \theta) \cdot External\,risk$ where $\theta \in [0, 1]$controls how much each model contributes to the overall term.

Heuristically we could think of the land locations being ranked by their increasing distance from their respective major external source of light pollution: urban < suburban < rural < protected land. In other words, the urban area is the least distant from its external light source — this distance is 0 as there is practically no source brighter than the city besides itself. Thus its **internal risk** term should dominate. Protected lands are the most distant from its external light source — the distance is a weighted term of all the displacements from the handful of cities nearby that could contribute a sizable amount of light pollution towards this protected land. Thus Protected land should assign its **external risk** a higher θ value.

7 Evaluating Risk at different land types

7.1 Urban Community - New York City

Key features: both indoor and outdoor light pollution contributing to human health

$$\text{Overall risk} = \text{Internal risk} + \text{External risk} = 53.79883 + 4.399$$

For such a highly populated cities of financial and political importance, we emphasized the risk of human health in Model I by adjusting the balancing value b^* to 10000, and by proportionally increasing the likelihood of residential light use leading to health issues to 95%. We also amplify the likelihood for commercial and traffic light usage, as the culture of night life lays the social condition that orients people to stay awake after their normal rest hours. Lastly, because it is unlikely for NYC to experience external risk from a nearby city, we upgrade the θ to 0.95.

7.2 Suburban Community - Ramat Gan

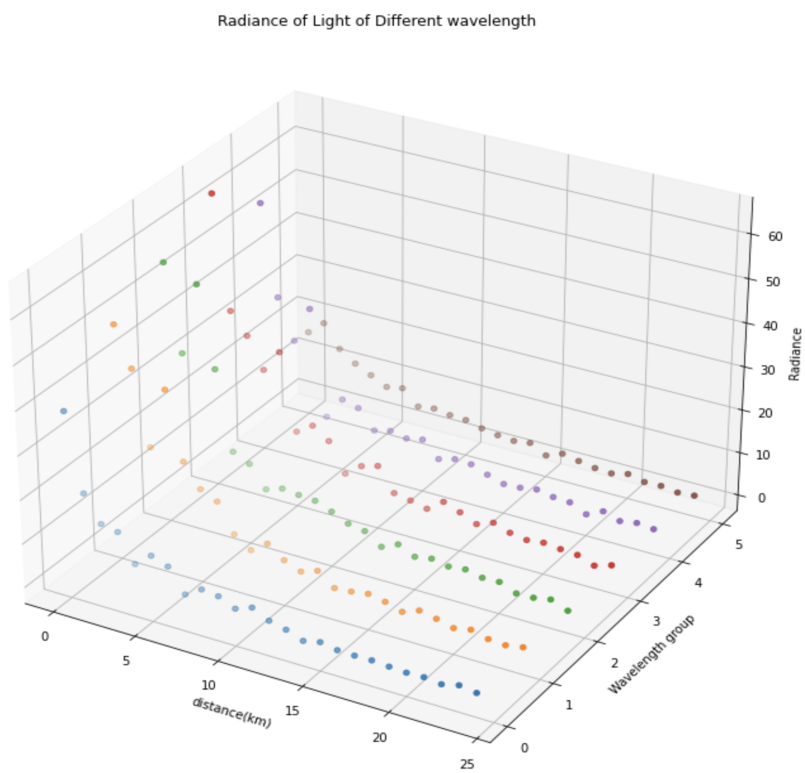

Figure 9: How different wavelength propagate impact over distances

Key features: birds' migration path going through the suburban community; large urban city nearby; fast-growing developments; heavy aerosol concentration.

$$\text{Overall risk} = \text{Internal risk} + \text{External risk} = 14.62734 + 22.299$$

Ramat Gan is a mid-size suburban region that is home for a wide variety of bird species, including sparrows, pigeons, and doves. According to existing biological research, lights from wavelength 400 nm to 550 nm are especially harmful to these birds because it can alter their foraging patterns, making them spend more time in their nests, and causing reduced immune function. With this information, we ran our model II with new risk indices assigned to each wavelength bracket, with 0.23 assigned to lights from wavelength 400 to 550, and 0.1 assigned to the rest. Then we ran our external radiation impact model and found the resulting impact 411% timers stronger than assigning a uniform weight to all lights. This significant increase in the risk factor is the result of blue and green wavelengths being scattered much more than the rest from the visible spectrum, and the sea-level altitude of Ramat Gan contributes to stronger scattering effects.

The major cities close to Ramat Gan include Tel Aviv. Based on its past GDP growth rate, Tel Aviv is expected to experience an increasing rate of economic development, which would spur construction of many shopping malls and recreational facilities. Based on the current trend, these new additions are expected to increase the city radius by 3.5% and aerosol production by 8.1% in our model II. Further, since Tel Aviv is a coastal city, the amount of light produced would produce an expected harm 23% higher than a non-coastal city. This places Ramat Gan in an especially high external risk of suffering from the detrimental effects of light pollution.

7.3 Rural Community - Florida Everglades

Key features: rural area with light-sensitive algaes; tourism destination; large urban city nearby

$$\text{Overall risk} = \text{Internal risk} + \text{External risk} = 1.52925 + 17.839$$

Florida Everglades is a 1.5 million-acre rural area housing a diverse range of plant and animal species. The overgrowth of algae is a threat but maintains an equilibrium with the ecosystem. Thus its growth instability due to night-time illumination by the nearby city, Fort Lauderdale, could tilt the balance to either side. Like what we did for birds, the wavelength between 640 nm and 700 nm is the target bracket we adjusted our model II on by upsizing its risk indices to 0.46, which is doubled amount of that we assigned for birds, as we account for the temporal and spatial magnitude of the potential impact on the plant families. Meanwhile in model I we tune down the balancing weight for human over non-human effects and promote the likelihood of tourism activities causing internal risks to 80%.

7.4 Protected Land Area - Kitt Peak National Observatory

Key features: protected land with an observatory susceptible to skyglow coming from the combined direction of two large cities nearby

$$\text{Overall risk} = \text{Internal risk} + \text{External risk} = 0 + 0.29881$$

The Kitt Peak National Observatory is located in the Quinlan Mountains, 50 miles southwest of Tucson and 100 miles south of Phoenix. The two cities both are attractions with a stable population of 0.5 and 1.7 millions respectively. Running model II by superposing the light radiation effects from both south and southwest, we found that the risk value, 0.29881, is slightly higher than 0.29804, the sum of the external risks due to the two cities when computed separately. This is due to the fact that model II considers the range of affected directions, and thus stressing the regions between angles made by the two cities.

The high altitude of the observatory, that of 6888 feets, discounts the effect of light scattering as our model II is most accurate for near-ground approximations.

8 Strategies to mitigate light pollution

For possible strategies to mitigate light pollution, we proposed a strategy that varies on a scale from the least intense to the most intense since we believe that in order for bigger impacts to be made, a more intense type of strategy needs to be proposed. Yet with an intense action needed, the difficulty of implementation is also higher. We therefore devise the Favorable-Recommended-Mandatory Strategy line and propose possible actions that help with light pollution.

8.1 Favorable

Our ranking of strategies revolve around the difficulties of implementation, therefore our Favorable tier are all actions people can take personally to decrease the light pollution in an area. Some examples of such actions are:

- **Education Programs**: Since light pollution and its effects are still unfamiliar terms to the greater public beyond scientists, thus it's crucial to establish education programs or feature articles on bigger platforms like local news and social media. Even if a percentile of the public took action, in the long run it will lead to more knowledge on the issue.
- **Restricting activities to daytime only**: natural darkness is precious for some activities such as photography and art, and the effects can not be replicated with artificial light. Therefore, it is better to restrict activities that can be done under both natural light and artificial light to daytime only in order to preserve the darkness that many treasure. It also decreases commercial usage of light in general and is beneficial to humans and animals alike.

- **Shields for light trespass:** This is very essential on a personal level, since the level of difficulty is especially low. By adding shields to windows in both commercial and residential buildings during the night time, privacy can be protected and it is also better for cities on the path of animal migration.

8.2 Recommended

Our recommended strategies are focused around lowering light usage in general on a policy basis. In order to accomplish this, a curfew or a limited usage of light is needed.

- **Curfew:** This can be implemented for non commercial or industrial activities, which cuts out most unnecessary usage of light. Furthermore, this cuts down the electricity usage as well which in turn conserves energy. This is especially effective since humans need darkness in order to get their bodies into “night mode” to stay healthy.
- **Limiting light usage for Industrial and Commercial use:** Since we are aware it is unrealistic to cut out light use for certain human development and activities, we can implement a light usage schedule for those businesses that need light in to function. While not cutting out light use entirely, it can still drastically decrease light pollution in general.

8.3 Mandatory

Since the development of technology advances at such a great speed, it is necessary to change some of the age old designs of lights as well, hence the main argument for the mandatory rank strategy is to reduce light pollution by changing certain traditional components to make them fit for a modern society while respecting traditions.

- **Dimmable Light Bulbs**: This design is already fairly old but it has yet to be implemented in every household. Without cutting out light usage entirely, one can adjust the level of brightness with respect to their own demands, and they can also adjust the levels based on outside lighting as well.
- **Tree planting alongside street lighting:** In addition to modifying the designs of individual street lamps, we can also consider other ways to shield the lamps so that the amount of vertical light is dampened or absorbed by trees nearby. That way, the reflection of light which is unnecessary can be minimalized, which in turn helps decrease sky glow.
- **Minimizing decorative lighting:** We understand that preserving traditions is a very important factor for human civilization as a whole and celebration activities are important for many cultures, so we do not want to cut it out entirely. However, decorative lighting is a consistent presence even when times for celebratory activities are over, therefore it is an unnecessary light source. By taking them down when they aren’t needed, we can also see a significant change in the risk of light pollution.
- **Use more filtered lighting:** As we considered the problem, we realized that only a specific set of wavelengths are harmful to humans and animals, therefore by using filtered lighting, we are doing a favor to both our own health and animals that reside around in the area.

9 Effectiveness of Our Strategies

9.1 Effectiveness of strategies in an urban setting - New York City

The top strategy is: limiting commercial light usage by taxing more for operations past a certain hour.

Justification: The principled risk factors are indoor light usage and social tendencies to stay up. The prevalence of these two causes are great and their likelihood of causing health issues are the highest. Thus we want a policy that could drop the likelihood while ensuring the highest possible coverage rate, while taking into consideration the difficulty of policy-making. Reducing commercial light usage after sunset by 50% parallelly translates into a reduction in the internal risk score from 53.79883 to 20.8900. This disproportionate reduction can be explained away by the network effect of a healthier post-sunset lifestyle.

9.2 Effectiveness of strategies in the suburban setting - Ramat Gan

The top strategy is: Curfew at selected periods of the year.

Justification: The principled risk factor of our analysis is the amount of bird deaths during their mass migrations, which take place in a predictable 10-day period in Spring and in Fall. As shown by our model II for external factors, issues during migration are caused by the illumination of the sky, when integrated for the total effective area, triples that of the area of the nearby city itself. Thus an effective measure on a mass scale is most appreciated. City-wide curfew for 10 days is expected to bring down the yearly risk score by 68%, eliminating the amount of risk attributable to bird deaths and related consequences on biodiversity in the habitats around Ramat Gan.

10 Strengths and Weaknesses

10.1 Strengths

- Our model allows a rigorous analysis of scattering of light of different wavelengths, by separating the effects due to the Rayleigh Scattering and Mie Debye Scattering. Moreover, in protected areas where the local fauna and fauna are especially vulnerable to light of a specific wavelength (for example, migratory birds on blue/violet lights), our model can be implemented with the corresponding risk analysis.
- Our model considers the different surface types and is especially important for coastal cities and the protection of marine life.
- Our model is easily integrable with other economic development models. With respect to economic growth, we found a strong correlation between the GDP of the city and the amount of aerosol particles present, and our model allows us to predict how much more light pollution would be produced and how much more vulnerable the animals would become given the economic agenda of the city.

- Compared to previous models which assume a point light source or a circle of uniform intensity, our external physical model, which supposes a core, inner circle with uniform luminance surrounded by areas whose luminance is exponentially decaying is more sophisticated and realistic.
- Compared to the use of satellite images as a measure of light pollution, our model has the following advantages:
    - Our model can distinguish the effects of superposition of light pollution;
    - Our model allows easily visualization of the effects of changing lamp design(e.g. switching from LED to fluorescent light, putting a cap on street lamps, etc);
    - Satellite only measures how much light is emitted from that area from a zenith perspective, and the amount of light pollution that one feels from the ground doesn't necessarily correspond to that(e.g. "induced" light sources)

10.2 Weaknesses

- Our models did not address geometric scattering(for particles much larger than the wavelength of visible spectrum, such as water droplets from clouds or large dust particles. Nor do we consider aerosol molecules that are small enough to cause Rayleigh scattering
- Our models did not consider humidity, temperature,or weather.
- Our models did not consider the effect of buildings or mountain range shielding.
- Our models did not address the effect of moon and other celestial objects
- Our models only work within a certain time period (relatively current)

11 Possible Improvements

For the weaknesses, we addressed several factors that we simplified due to the limitation of datasets, and the difficulty of calculation. However, our last weakness that addresses time concerns can possibly be improved. For all the causes and factors we are considering, if we have access to enough data, we can rewrite most as a function of time and using regression methods, the model can then become a predictive model and can be utilized to determine light pollution risks in the future.

One of the possible drawbacks is that we cannot predict when sudden changes in technology or uncontrollable events such as war or pandemics occur. Yet by still using regression, we can decrease the interval between each time data point and do further regression to slowly approach the time point or time frame in the future. We are aware the future is uncertain, yet by using smaller intervals, certain patterns can be observed.


TIME TO TURN OFF YOUR LIGHTS!
Illumination Control Mission(ICM)-urban program
BUY DIMMABLE LIGHT BULBS THAT HAVE DIFFERENT LIGHT SETTINGS SO YOU CAN ADJUST THE LEVEL BASED ON NATURAL LIGHT
PLANT TREES ALONG THE STREETS AND IMPLEMENT COVERED LIGHTS TO MINIMIZE THE AMOUNT OF VERTICAL LIGHT AND LIGHT REFLECTED OFF THE GROUND
DECORATIVE LIGHTINGS ARE FUN BUT THEIR IMPACT ON LIGHT POLLUTION IS NOT NEGLIGIBLE. LIMIT THE USAGE TO HOLIDAYS AND SPECIAL CELEBRATIONS
USE MORE FILTERED LIGHTS THAT LIMIT THE EMISSION OF BLUE LIGHTS(MAINLY) AND OTHER WAVELENGTHS THAT IMPACT MIGRATION OF BIRDS AND YOUR HEALTH.
You can help make this a reality!
Want to see what Van Gogh sees in the city?

Bibliography

[1] “Star Walk 2 - Best Astronomy App.” *Star Walk*, https://starwalk.space/en.

[2] “UGA Physics and Astronomy • Physics and Astronomy @ UGA.” *Physics and Astronomy*, 14 Feb. 2023, https://www.physast.uga.edu/.

[3] Bani Assadi, Saeedeh, and Kevin C. Fraser. “The Influence of Different Light Wavelengths of Anthropogenic Light at Night on Nestling Development and the Timing of Post-Fledge Movements in a Migratory Songbird.” *Frontiers*, Frontiers, 1 Oct. 2021, https://www.frontiersin.org/articles/10.3389/fevo.2021.735112/full.

[4] *IOPscience - Institute of Physics*. https://iopscience.iop.org/.

[5] “Light Pollution.” *International Dark-Sky Association*, 14 Feb. 2017, https://www.darksky.org/light-pollution/.

[6]“Light Pollution: The Overuse & Misuse of Artificial Light at Night.” *JMU*, 4 Jan. 2022, https://www.jmu.edu/planetarium/light-pollution.shtml.

[7]*Modeling Light Pollution from Population Data and Implications for* ...https://www.researchgate.net/publication/311693330_Modeling_Light_Pollution_from_Population_Data_and_Implications_for_National_Park_Service_Lands.

[8]“Maps and Results.” *Globe at Night*, https://globeatnight.org/maps.php.

[9]*Rapid Assessment of Lamp Spectrum to Quantify ... - Wiley Online Library*. https://onlinelibrary.wiley.com/doi/full/10.1002/jez.2184.

[10]“Explore Scientific, Technical, and Medical Research on ScienceDirect.” *ScienceDirect.com | Science, Health and Medical Journals, Full Text Articles and Books.*, https://www.sciencedirect.com/.

[11]Schwarz, Hugo E. *Light Pollution: The Global View: Proceedings of the International Conference on Light Pollution, La Serena, Chile, Held 5-7 March 2002*. Kluwer Academic Publishers, 2003.

[12]*Light Pollution around UGA's Observatory as Measured with an Iphone* ...https://www.physast.uga.edu/~zhaoy/Lightpollution.pdf.

[13]Bedrosian, T A, and R J Nelson. “Timing of Light Exposure Affects Mood and Brain Circuits.” *Nature News*, Nature Publishing Group, 31 Jan. 2017, https://www.nature.com/articles/tp2016262.

[14]Fishbein, Anna B., et al. “Circadian Disruption and Human Health.” *The Journal of Clinical Investigation*, American Society for Clinical Investigation, 7 Oct. 2021, https://www.jci.org/articles/view/148286.

[15]Author links open overlay panelCarolyn S. Burt 1, et al. “The Effects of Light Pollution on Migratory Animal Behavior.” *Trends in Ecology & Evolution*, Elsevier Current Trends, 5 Jan. 2023, https://www.sciencedirect.com/science/article/pii/S0169534722003329?via%3Dihub.

[16]Buldakov, Michail A., and Victor N. Cherepanov. “Polarizability Functions of the N2 and O2 Molecules.” *SPIE Digital Library*, SPIE, 27 Feb. 2004, https://www.spiedigitallibrary.org/conference-proceedings-of-spie/5396/1/Polarizability-functions-of-the-N2-and-O2-molecules/10.1117/12.548210.full?SSO=1.

[17]J. M. Haywood and K. P. Shine, "The Effect of Anthropogenic Aerosols on the Clear Sky Planetary Radiation Budget," Geophysical Research Letters, vol. 22, no. 5, pp. 603-606, March 1995.