A Methodology for Optimal Sensor Location of a Light Pollution Network

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Introduction

Large cities are heterogeneous; consequently, the urban space must be differentiated according to various criteria: the economic ones that determine the value of land, the social ones that imply a grouping by similarity,the environmental ones that allow to designate protected areas, among others.A correct approach to generate information on environmental problems in cities is by establishing monitoring networks. In occasions, the number of monitoring sensors may be limited, and researchers require a system that can collect as much information as possible with available resources.

Here we present a proposal on optimal sensor location of a light pollution monitoring network using nighttime and environmental-sensitivity satellite images. The nighttime image provides information to discriminate regions without significant light pollution, while the environmental-sensitivity image defines the features of the land use for assigning a hierarchy to protected, urban and industrial regions. First, both images are combined into a single one, named as *priority image*, that is the input to the local maxima identification process that finds potential sensor locations. Then, the locations are sorted by first assigning the sensors to the locations with the highest priority. This procedure benefits the most sensitive regions to light pollution and considers a constrained number of light sensors.

Nighttime light data are retrieved from the average stable light product provided by the National Geophysical Data Center and US Air Force Weather Agency [1]. The range of the image values is [0,63]. The highest values are, usually, located at the city center and at the commercial zones [2] where the urban development is more dense.

Method for Light Sensor Location

Assuming that the measured luminance data do not have saturation problems, and the environmental-sensitivity data are stored in matrices of the same shape using positive integers, we produce the optimal location map as follows:

1. First, to define the luminance and sensitivity inputs maps as L and S matrices respectively.
2. To compute the weight matrix W using the weighing equation $W = 4^S$.
3. Then, to calculate the priority matrix P with the Hadamard (element-wise) product using luminance and weight matrices $P = L \circ W$.
4. To obtain the list of candidate locations C that satisfies local optimality in a 4-pixel neighborhood.
5. To sort the elements in C according to their associated priority value in P.
6. To allocate the n sensors in the n locations according to the highest priority.

In the case that the luminance image presents saturation problems, we propose to replace the matrix L by a Gravitational Luminance Image Representation (GLIR) G and perform the same steps.

Gravitational Luminance Image Representation GLIR for saturated nighttime Images

The generation of non saturated light intensity satellite images is problematic due to limitations in the sensor design. Saturated nighttime images make difficult to identify a single local maximum within a defined neighborhood. Therefore, we propose a representation inspired on the Newton's Law of Gravitation to approximate the maximum values in saturated regions replacing the original luminance value by the sum $g_{i,j}$ defined in Equation 1. We call it Gravitational Luminance Image Representation (GLIR), and it is denoted by the matrix G. The GLIR represents the total gravitational force exerted on a location with mass m_i and it is calculated using the nighttime image L as the gravitational field. Then, the following Equation is used to transform L into G:

$$g_{i,j} = \sum_{x=i-h}^{i+h} \sum_{y=j-h}^{j+h} = \frac{m_i m_j}{d^2} \tag{1}$$

,

where $m_1 = L_{i,j}, m_2 = L_{x,y}$, $d = \sqrt{((x-i)^2 + (y-j)^2)}$ is the distance between two pixels, and h is a window size that constraints the computations in a neighborhood of size $(2h+1) \times (2h+1)$. This function produces a gravitational representation G, that reduces the saturation problem, while preserves the luminance local maxima in L with the highest priority. Thus, it is used to determine the location of maximum priority levels located in saturated areas.

Results

We applied the proposed method to the Queretaro Metropolitan Area, in central Mexico.

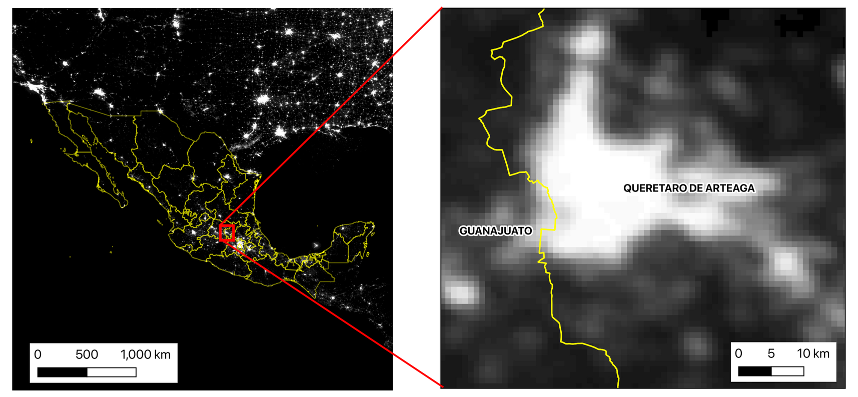

Figure 1: Study area and nighttime light image.

The implementation of the methodology is described graphically in Figure 2.

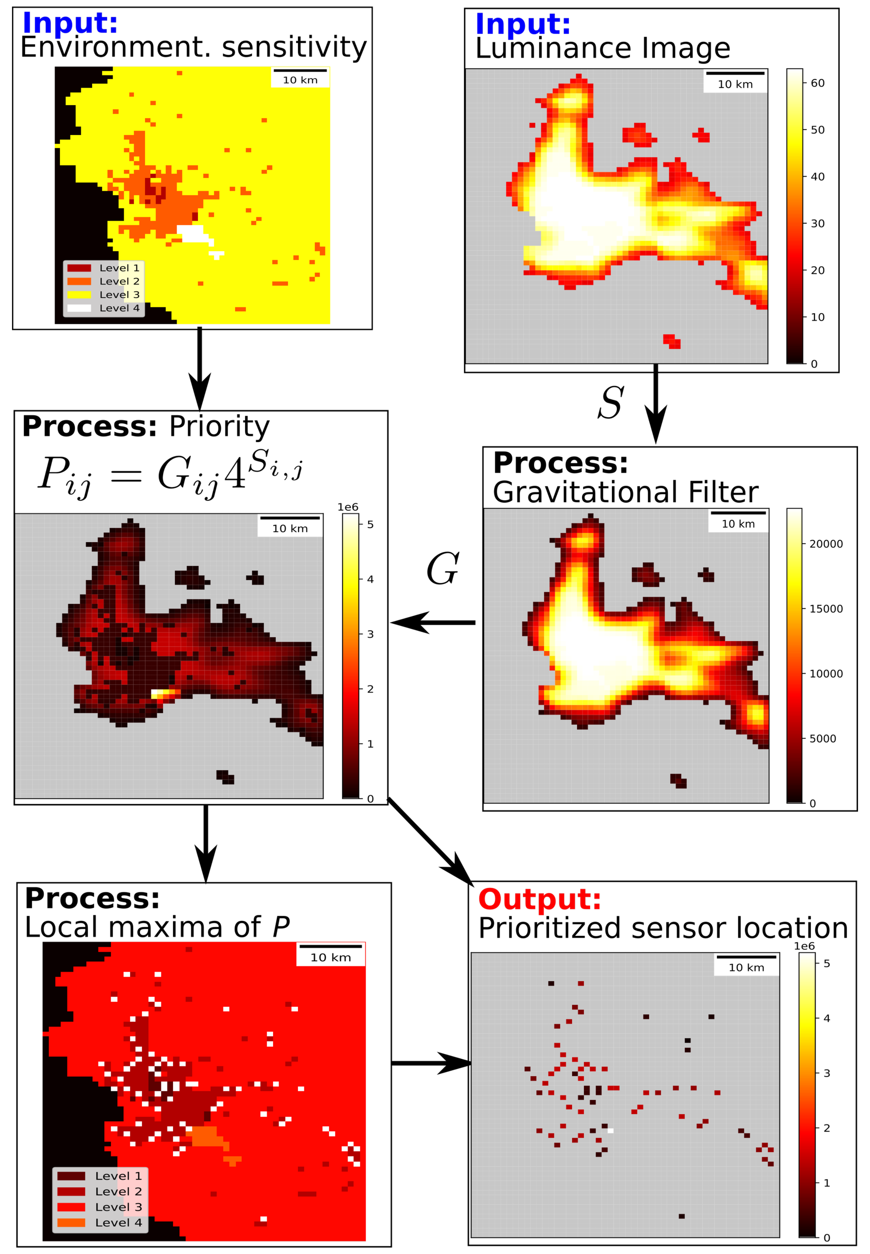

Figure 2: Implementation of the methodology

. The methodology highlighted a set of pixels with local maxima distributed in the region according to the priority matrix. These pixels were sorted according to the environmental sensitivity level combined with the luminance intensity. The proposed methodology allow us to automatically identify that the most important location for a light sensor is the nearest protected zone to the urban region with a high luminance level.

In Figure 3, we present two plots that show a measure of the amount of information of interest retrieved by n sensors.

The left plot presents the normalized and sorted priority values P associated with the candidate locations C and the right plot presents the cumulative curve of those priority values in the left plot.

In this exercise, the cumulative plot suggests that in order to monitoring the 80% of important information, we require to allocate $n = 39$ sensors.

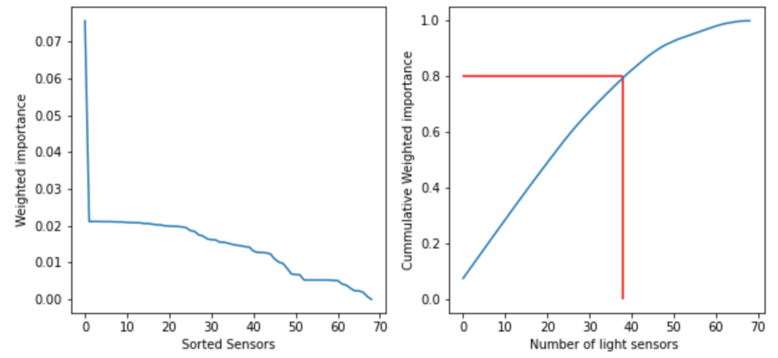

Figure 3: Sorted Normalized Importance and Cumulative importance curve

Conclusions

A city is considered an element of observation and measurement. It is configured as a differentiated space characterized by its population and the predominance of certain activities. For this reason, when establishing a monitoring network, these differences should be considered. Specifically, in light pollution, a monitoring network must be distributed according to the city's lighting needs. In this case, we consider two sources of information: luminance and environmental sensitivity, so the sensor locations consider the poles of attraction of the city; that is, the nodes where the pixels have a high value in the sources. We have shown that it is possible to have an efficient method for identifying the best areas of a city where to place light pollution sensors. The method not only permits to assign the sensors efficiently, but also to determine the amount of information that can be obtained when limited number of experimental devices are on disposal. We hope that this method can support light pollution research.

References

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[2] Kang Wu and Xiaonan Wang. Aligning pixel values of dmsp and viirs nighttime light images to evaluate urban dynamics. *Remote Sensing*, 11(12):1463, 2019.

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