

Modelling of light pollution in suburban areas using remotely sensed imagery and GIS

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Abstract

This paper describes a methodology for modelling light pollution using geographical information systems (GIS) and remote sensing (RS) technology. The proposed approach attempts to address the issue of environmental assessment in sensitive suburban areas. The modern way of life in developing countries is conducive to environmental degradation in urban and suburban areas. One specific parameter for this degradation is light pollution due to intense artificial night lighting. This paper aims to assess this parameter for the Athens metropolitan area, using modern analytical and data capturing technologies. For this purpose, night-time satellite images and analogue maps have been used in order to create the spatial database of the GIS for the study area. Using GIS advanced analytical functionality, visibility analysis was implemented. The outputs for this analysis are a series of maps reflecting direct and indirect light pollution around the city of Athens. Direct light pollution corresponds to optical contact with artificial night light sources, while indirect light pollution corresponds to optical contact with the sky glow above the city. Additionally, the assessment of light pollution in different periods allows for dynamic evaluation of the phenomenon. The case study demonstrates high levels of light pollution in Athens suburban areas and its increase over the last decade.

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1. Introduction

Night light emissions that originate mainly from large urban areas are among the main elements of environmental pollution. The rapid growth of night sky brightness due to light pollution is not only damaging the perception of the starry sky, but is also silently altering even the perception of moonlit nights by mankind (Cinzano et al., 2001a).

Astronomers are among the worst affected by urban sky glow (IDSA, 1996; Falchi and Cinzano, 2000), but environmentalists are also worried about the direct effects on wildlife, as well as the reduction in the overall ‘quality of life’ for the people of Europe. Among the negative effects of light pollution are: (i) disturbance of biological rhythms,

(ii) psychological effects, and (iii) environmental degradation (Shaflik, 1997; Borg, 1996).

Over the last decades, many scientists have modelled light pollution in various ways, e.g. creating maps showing the sky glow variation at different altitudes and azimuths from different observation sites (Garstang, 1986), mapping artificial sky brightness in large territories (Cinzano et al., 2000; Cinzano et al., 2001b), spatial population definition using DMSP-OLS data (Elvidge et al., 1997), or urban area mapping (Imhoff et al., 1997). The interest in light pollution has been growing in many fields of science, extending from the traditional field of astronomy to atmospheric physics, environmental sciences, natural sciences and even human sciences (Cinzano et al., 2001a,b; Doll et al., 2000), although the Greek literature on the issue is rather limited (Chalkias et al., 2002).

Artificial lighting disturbs the ‘tranquility’ (grade of naturalness) of an area. This kind of pollution is directly correlated to the presence of human activities and for this reason is considered of high interest. Tranquility maps are a valuable tool for the classification of parts of the countryside, as well as for the classification of areas that are

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relatively undisturbed by noise and visual intrusion, areas representative of ‘unspoiled’ countryside.

Tranquility can be defined as ‘the sense of peace, quiet and natural pureness of the countryside’ (Bell, 1999). The main factors that disturb tranquility are:

- light pollution (buildings, human constructions, artificial lighting, etc.)
- noise pollution (road traffic, industry, railroads, etc.)
- absence of woodland.

While tranquility disturbance is profound in modern urban areas, suburban and rural areas also face the same problems due to urban growth, intense cultivation activities, transportation network expansion, etc.

This study was conducted within the framework of the European project MANTLE (mapping night-time light emissions). The main target of the MANTLE project was to assess the potential of using satellite resources to produce maps of light emissions and urban night-time light intensity levels in the EU.

The scope of this study is to develop and present a prototype methodology for modelling light pollution, as well as to estimate the grade of light pollution in Athens suburban areas by creating various corresponding maps.

2. Data-methodology

For the night light emission study, satellite data were used from the Defense Meteorological Satellite Program (DMSP)/OLS: Operational Linescan System of the USA. The DMSP satellites, with the onboard OLS, have the capability to detect faint sources of visible near-infrared (VNIR) emissions on the Earth’s surface, making it possible to detect cities and towns (Elvidge et al., 1997; Croft, 1978). This capability allows the mapping of urban night-time light emissions (upward light emissions) from terrestrial sources. Since, optical satellite images depend on the meteorological conditions (cloud coverage), the selection of suitable images is restricted to a number of favourable nights.

DMSP uses satellites of the National Oceanic and Atmospheric Administration (NOAA) in low altitude (830 km) sun-synchronous polar orbit with an orbital period of 101 min. Visible and infrared imagery from DMSP/OLS instruments monitor the distribution of clouds all over the world twice a day, once during daytime and once at night (Cinzano et al., 1999). The OLS radiometer consists of two telescopes and a photo multiplier tube (PMT). The visible telescope is sensitive to radiation from 0.4 to 1.1 μm . The PMT is sensitive to radiation from 0.47 to 0.95 μm , with highest sensitivity at 0.55–0.65 μm , where the most frequently used lamps for external night-time lighting have the strongest emission. Telescope pixel values are replaced by PMT values at night.

The available DMSP data for this study cover the period 1994–2002. The spatial resolution of the images is 0.47 km at high resolution (fine mode) and 2.7 km at low resolution (smooth mode), while visible values are relative values ranging from 0 to 63 (6 bit) and infrared pixel values correspond to a temperature range of 190–310 K in 256 equally spaced steps (DMSP/OLS, 2004). These features make DMSP data convenient for regional scale studies. All the images used in this study have been georeferenced to the local Hellenic Geodetic Reference System (HGRS 87). The processing of the satellite images was performed using ERDAS and Arc GIS software in order to eliminate noise and also to eliminate problems emanating from ephemeral night light sources (e.g. forest fires).

The technological context of the proposed approach includes GIS and RS techniques, as well as satellite data relevant to night light emissions. The main source of these data is DMSP images (Fig. 1).

These data are the core of the spatial database created. As mentioned above, in order to produce representative images and eliminate noise effects, multiple images of the same period have been combined using cartographic overlay techniques. This processing includes the following steps: (i) geometric and radiometric processing of DMSP images, (ii) identification of cloud-free images based on OLS-IR data and (iii) filtering of selected images based on frequency in order to remove ephemeral events (Cinzano et al., 2000). The creation of representative images for each period was implemented according to the following steps (Fig. 2): firstly, the optical interpretation of infrared images helps to depict the proper cloud-free VNIR images for further analysis. From this set of night light images, we overlaid images from the same period (e.g. winter 2000), using local statistical cartographical overlay functions (Tomlin, 1990) in order to investigate ephemeral night light sources. The general concept was to maintain the most frequent values (generally close to the mean value) for each pixel and reject extreme values. The last step was the creation of representative night light images using maintained values. The final products are cloud-free composite summer and winter season images for the period between 1994 and 2001. Over 150 images have been combined in order to produce 16 composite images.

The other part of the GIS spatial database consists of basic cartographic data coming from analogue maps and other RS imagery: the road network, topography, stream network and land cover (CEC CORINE program, 1993).

One of the most important data sets in this study is the digital elevation model (DEM) of the study area (Attica region). This model has been created using the ANUDEM algorithm from captured elevation contours and other supplementary data (elevation spots and streams) (Hutchinson, 1989; ESRI, 1995). The main sources of elevation data were analogue maps from the Hellenic Military Geographical Service (scale 1:25,000). The DEM produced

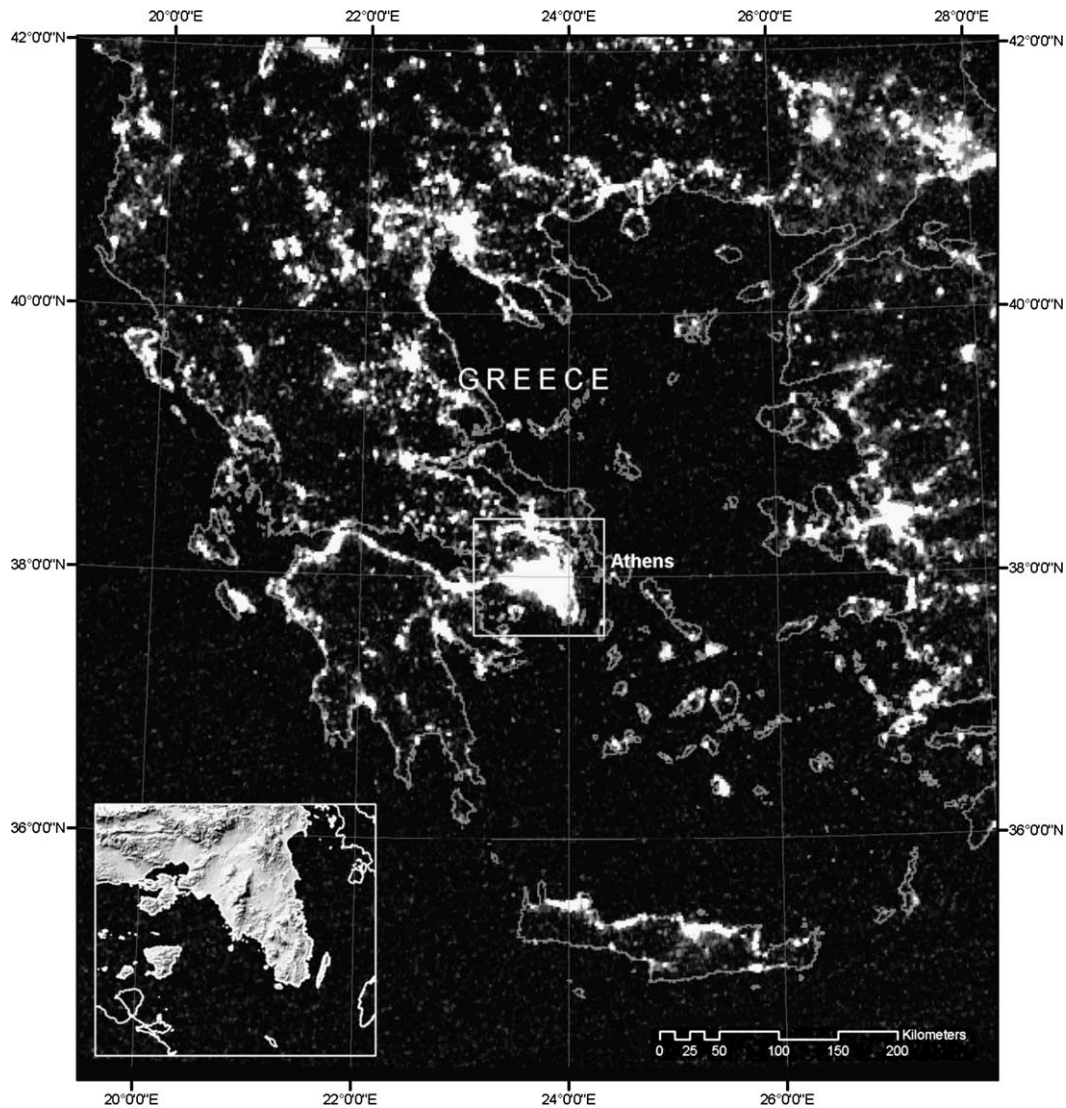


Fig. 1. Night-time light emissions over Greece on 19/09/2001.

was in grid format with 50 m cell size and with horizontal and vertical RMSE < 25 m. The processing of DEM has significantly reduced the time necessary to create viewshed maps. The creation of these maps in a GIS spatial analysis context is a process involving a DEM and a map containing point locations (points of observation), or locations from which the viewshed is calculated (ESRI, 1995). Moreover, we can quantify the number of observation points with direct visual contact with all the locations of the area, which correspond to the cell centers of the DEM. In this study, night light emission locations were treated as observation points.

3. Analysis

Our main intention was to identify the amount of light pollution due to artificial nightlights, in the greater Athens area and estimate the grade of light pollution in suburban

areas. Two basic parameters of light pollution were studied. The first concerns direct visual contact with nightlights, while second involves indirect light pollution (visual contact with the sky glow dome over the Athens

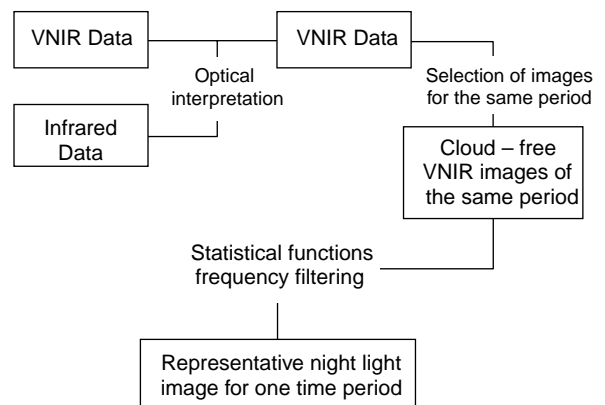


Fig. 2. Creation of representative image for one period.

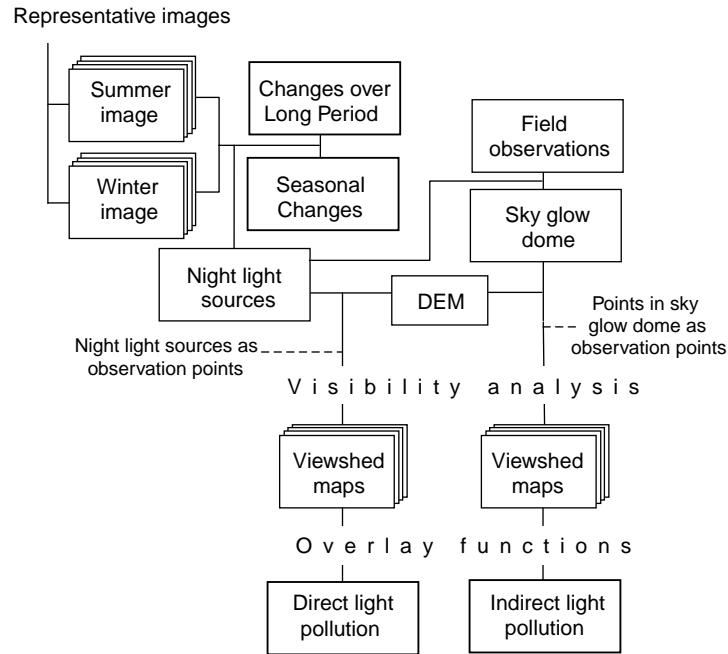


Fig. 3. Flow-chart of the proposed methodology.

metropolitan area). Fig. 3 presents the basic stages, as well as the data flow of the proposed methodology.

3.1. Direct light pollution

The aim of this approach was to investigate and quantify the amount of direct visual contact between an observer and nightlights from Athens, using the appropriate satellite imagery (DMSP data), as well as the DEM of the study area.

Modern GIS packages offer advanced tools for visibility analysis (Burrough and McDonnell, 1998), including line of sight estimations and viewshed mapping. The viewshed identifies the cells in an input raster that can be seen from one or more observation points. Each cell in the output raster receives a value that indicates how many observation points can see the specific cell. The main intention was to perform visibility analysis considering night light sources as observation points (since visibility is a mutual spatial relationship). Points of night lighting were extracted from DMSP data. Points inside cells with high light emissions were identified as areas with significant artificial nightlight emissions. Using the GIS visibility analysis functionality the number of cells of light emissions, which are visible from each cell of DEM were estimated. The product was an output raster with cell values representing the total amount of visible observation points (Fig. 4). The final step was the classification of the output raster in order to determine areas with low to high direct visibility of night light emissions.

With the approach described above, we can also investigate temporal variations in disturbance due to nightlights, using time series of DMSP data. Fig. 5 shows the changes of direct night light pollution in the broader

Athens area for the period 1994–2001. The general increment trend in all suburban areas and also the major changes in the eastern part of the area because of the infrastructure development in the vicinity of the new international airport can be noticed. It is estimated that the total area of night light pollution increment during this period is more than 500 Km², corresponding to 10% of the study area.

3.2. Indirect light pollution

This second approach to light pollution assessment goes further than the direct visual contact between observers and artificial lights and tries to identify areas affected with indirect light pollution. By indirect light pollution we mean visual contact with the sky glow existing above the Athens area due to city lights. The key point in this approach is the identification of sky glow geometry. Many researchers have dealt with this problem using a variety of different approaches (Walker, 1977; Garstang, 2000). In this study, the estimation of sky glow dome geometry was made through field observations.

The basic assumption in this approach is isotropic sky glow development around Athens. Thus, light measurements of the Athens sky have been taken from remote sites using a sensitive light-meter of 3 cm diameter, monitoring E in mlux. The light-meter was placed on a theodolite in order to track the spatial changes of E. The same measurements have been taken at various observation azimuths from each site (Fig. 6).

The interpretation of these measurements allows the estimation of the height of the sky glow dome for each

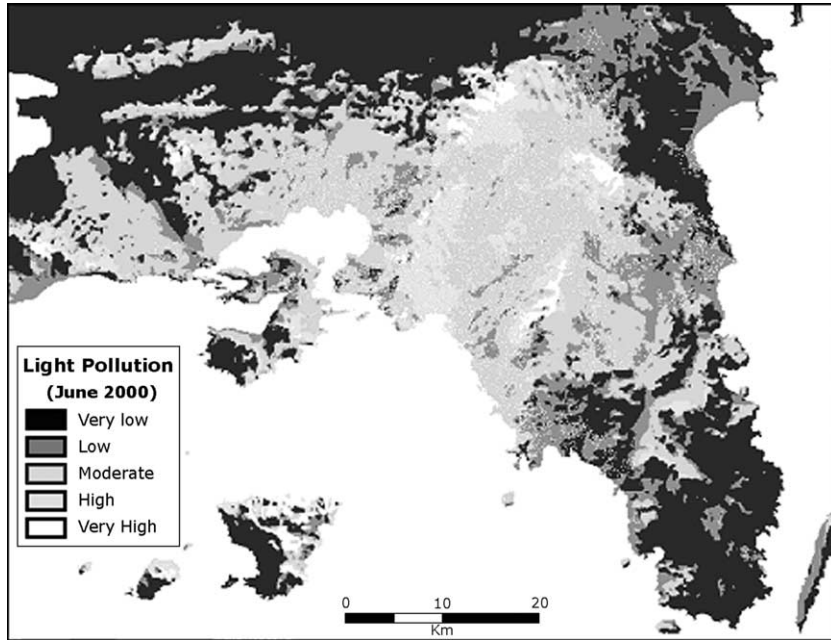


Fig. 4. Direct light pollution map (Summer 2000).

observation azimuth. This height is reduced as the observation line moves from the city center to the suburbs. Using these measurements, the correlation between distance from the city center and sky glow height was calculated.

From the combination of the sky glow heights and DEM, a complex surface was produced, the 'sky glow extended

topographic surface'. The next step was visibility analysis, assuming as observation points the points of the sky glow surface. The output grid quantifies the indirect light pollution, representing the areas where the observer has direct optical contact with the sky glow (viewsheds). The number of pixels visible from each point of the DEM corresponds to the grade of its indirect light pollution

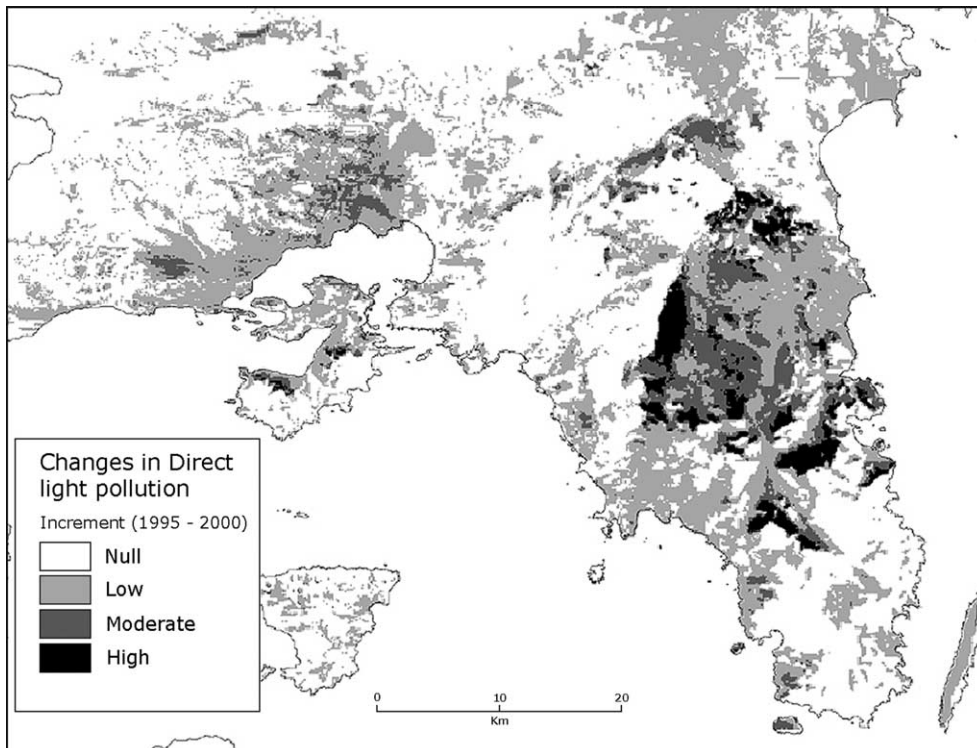


Fig. 5. Changes in direct light pollution for the period (1995–2000).

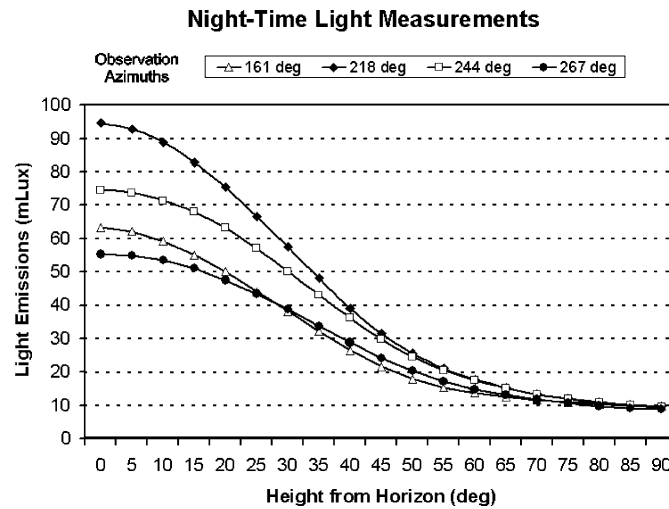


Fig. 6. Night light field measurements, observation site: Koufos hill, Penteli, E 23.86°, N 38.05°, height: 509 m a.m.s.l, 8th August 2002.

(Fig. 7). It must be pointed out that this is a time-consuming iterative approach, demanding large amount of computational power.

The methodology described above produces a number of maps and perspective 3D diagrams reflecting light pollution. These maps depict the amount of visual contact between light sources and locations of the study area. In general, a significant increase of light pollution in Athens suburban areas can be noticed. Isolated areas with limited disturbance are located mainly at the southern and eastern part of the Attica region, as well as near and around mountains. It is important to protect the pureness of the environment in these areas, as they are the most tranquil regions in the Athens metropolitan area according to their grade of light pollution.

4. Conclusions

The proposed methodology is an application of RS and GIS technology in the assessment of light pollution. DMSP data relevant to nightlight pollution and DEM are the main data sets of the study. The analysis of these datasets using and enhancing GIS functionality produces maps of direct and indirect light pollution. These maps provide decision makers and researchers with useful information about the spatial dispersion of disturbed and relatively tranquil areas in the countryside.

The analysis of night light data for the greater Athens region indicates a significant increase in direct light pollution during the last decade (10% of the total area investigated). At the same time, no more than 8% of

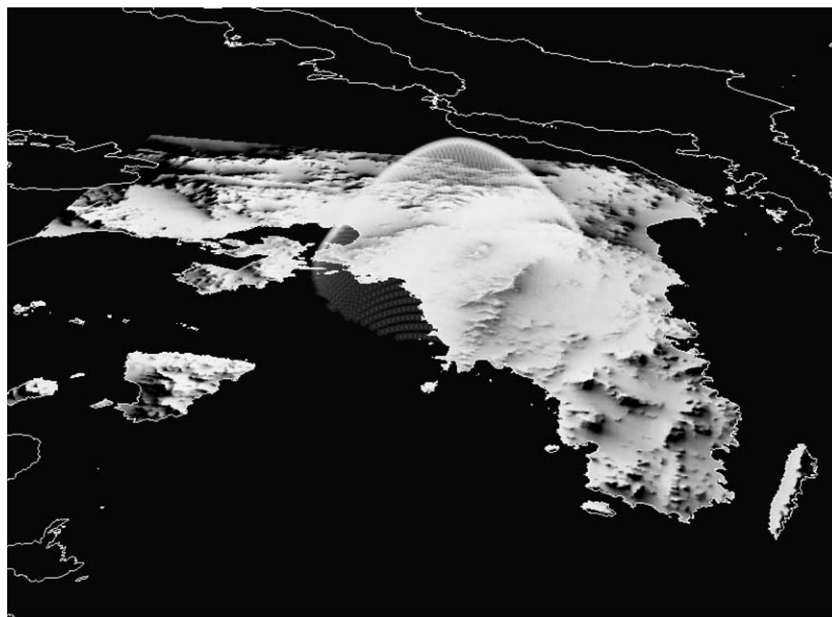


Fig. 7. Indirect light pollution (Summer 2000). Light tones correspond to high-pollution areas while dark tones to areas with low levels of pollution.

the study area enjoyed low levels of indirect light pollution. Large amounts of suburban areas are suffering from both direct and indirect light pollution, while tranquil areas are located mainly in restricted regions where mountains play the role of a visual barrier.

Future work will focus on the application of the methodology for all the area of Greece and the development of an integrated tranquility mapping procedure using additional impact factors (settlements, industries, road network, vegetation) for the estimation of the tranquility zones.

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