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Modeling Light Pollution from Population Data and Implications for National Park Service Lands

Introduction

There are many factors that affect nighttime sky brightness, both natural and human-made. It is useful to think of what the main light sources are and how this light is scattered. The natural sources come from stars, the Milky Way, airglow, and moonlight. Human-made sources include streetlights and other outdoor lights, concentrated largely in towns and cities. Light is scattered by air molecules, natural and anthropogenic particulates, and haze (an enlargement of these particulates related to atmospheric moisture). The result of all these factors is what we see at night in terms of the sky brightness. To help clarify the further discussion, some simplifications will be helpful. We will assume no moonlight and relatively low levels of particulates and haze—in other words, that we are looking at the night sky under conditions that are among the best for a given location. We also neglect things such as surface albedo, which affects how much light is directed upward from city lights. The main remaining factor is city lights, whose effect is approximately related to population, and natural airglow (a continuous aurora-like glow) that actually varies during the course of the sunspot cycle. The darkest sites on earth have a brighter glow than those in outer space for two main reasons: the scattering of starlight by the atmosphere, and airglow.

Brief Review of Previous Modeling Efforts

A number of people have modeled light pollution in various ways. As an example, Garstang (1986) has done detailed calculations for a number of observatory sites, creating maps showing how the skyglow varies at different altitudes and azimuths from each site. Burton (2000) is analyzing satellite data from the Defense Meteorological Satellite Program (DMSP; run by the U.S. Air Force) to estimate skyglow in the close vicinity of urban areas. This has the advantage of considering actual satellite data at high resolution, both spatially and in terms of intensity. However, limited consideration is given to atmospheric scattering, especially over large distances.

DMSP data have been linked with

a robust scattering model in Europe by Cinzano et. al. (2000, 2001). When properly calibrated, this provides greater spatial information about the sources of light pollution than population data alone.

Description of the Model

Assumptions and data source. The present effort is unique in that it produces an areal map of zenithal sky brightness over the entire USA. It works both within and at large distances from urban centers. The model also employs assumptions about scattering embodied in Walker's Law, with additional consideration of the earth's curvature. The model is based on the location and population (1990 census) of significant U.S. cities and towns (over 50 population).

Mechanics of the model. The model creates a map of expected skyglow at the zenith. For each location in the map, the light pollution contribution from each city is assumed to be related linearly to the population and the inverse 2.5 power of the distance. This is similar to the relation used in Walker's law (Walker 1977), except that we are estimating light pollution at the zenith instead of 45 degrees high in the azimuth of the brightest city. The relation used here for each city ***i*** is in equation 1, where

$$I_i = 11{,}300{,}000pr^{-2.5} \quad (1)$$

I_i is sky glow in nanoLamberts, p is the city population, and r is the distance to the city in meters. This is corrected for earth's curvature at large distances (this necessity was pointed out by Garstang). The correction is done by calculating the fraction f of the air molecules and other scatterers over the observer that lie above the earth's shadow that is formed from light traveling in a straight line from the city. The overall scale height s for these scatterers (defined as the altitude increase required to see a drop-off by a factor of *e*) is currently set to 4,000 m. This is less than the "clear air" value of 8,000 m accounting for a typical amount of aerosols. The scattering from this mixture is more strongly concentrated at low altitudes than that from air molecules alone.

$$f = e^{-h/s} \quad (2)$$

The height h is the amount of the air column above the observing location that is not in a direct line of sight to the light-polluting city due to the curvature of the earth. Adding this correction term f into equation 1 yields a further modified form of Walker's law as shown in equation 3.

$$I_i = 11300000pr^{-2.5}f \quad (3)$$

Finally the light pollution from each city is summed to get the total artificial skyglow I at a given location on the light pollution map as in equation 4.

$$I = \text{summation } I_i \quad (4)$$

A number of other ideas and equations used come from publications by Garstang. The assumed radius of each city is a function of city population, ranging from 2.5 km to 24 km. Walker's law applies if we are outside the city radius. Inside the city radius, the sky glow increases linearly toward the center by another factor of 2.5.

A value for the natural skyglow is added onto the light pollution contribution. The natural skyglow is assumed to be equal to 60 nanoLamberts (V = 21.9 mag / sq sec) at solar minimum. The last step in arriving at a pixel value is scaling the brightness with respect to the logarithm of the skyglow. The brightest city has pixel values of (255,255,255), and the darkest country site has pixel values of (42,52,67). The calibration bar is intended to linearly represent the sky brightness in terms of magnitudes per square arcsec. The model result is shown in Figures 1 and 2.

Schaaf Sky Quality Scale. Fred Schaaf has provided much helpful discussion that has led to substantial improvements in this image. As part of the calibration process of the image, we are comparing the expected amount of light pollution for various locations with observations of limiting magnitude and sky quality according to the Schaaf scale (Table 1; Schaaf 1994).

Figure 1. Modeled skyglow over the continental USA.

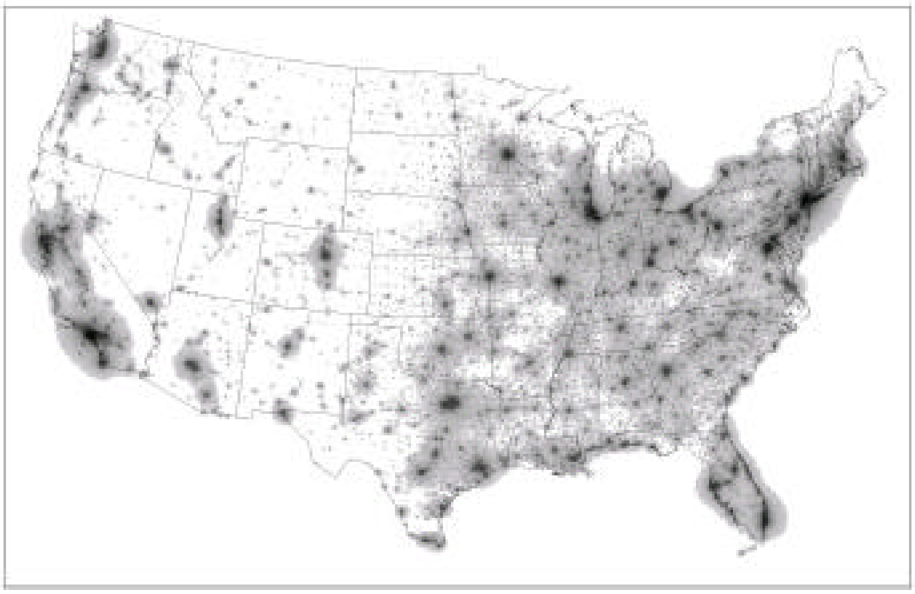

Figure 2. The shadings here are rescaled from Figure 1 to represent the seven-level Schaaf scale.

Table 1. The Schaaf scale and Zenith Limiting Magnitude (ZLM) equivalents. Within the context of this light pollution model, the above conversion can be done between Schaaf scale and ZLM. This has been modified slightly from the original scale so that the verbal sky descriptions in the Schaaf scale are more consistent with modeled limiting magnitudes.

Schaaf Class	*Zenithal Limiting Magnitude*
1	<4.75
2	4.75-5.25
3	5.25-5.75
4	5.75-6.20
5	6.20-6.55
6	6.55-6.76
7	6.76-6.81

Verification of the model with observations. Field data have been received from locations throughout the USA, primarily from the International Meteorological Organization. These data are in the form of zenith limiting magnitude, and can be compared with values predicted by the model for the same location. Figure 3 is a scatter plot of observations received near sunspot maximum compared with predicted limiting magnitude for the site. The graph shows that the predicted values are in relatively good agreement with those observed, especially between magnitudes 5 and 6. For very dark skies, observers typically do not see stars as faint as the model predicts, and for brighter skies, observers consistently see stars fainter than the model predicts.

Future Work

A natural extension of this work would be to incorporate DMSP data, perhaps along with the population data, to gain a better idea of where the light sources are in the USA. This has been done for Europe and may be extended to other parts of the world by Cinzano et. al. (2001). The use of population data from other census decades could provide a time series of light pollution in the USA over many years.

National Park Land Area Analysis

The model may be used to evaluate the effects of light pollution on areas administered by the National Park Service (NPS) for the purpose

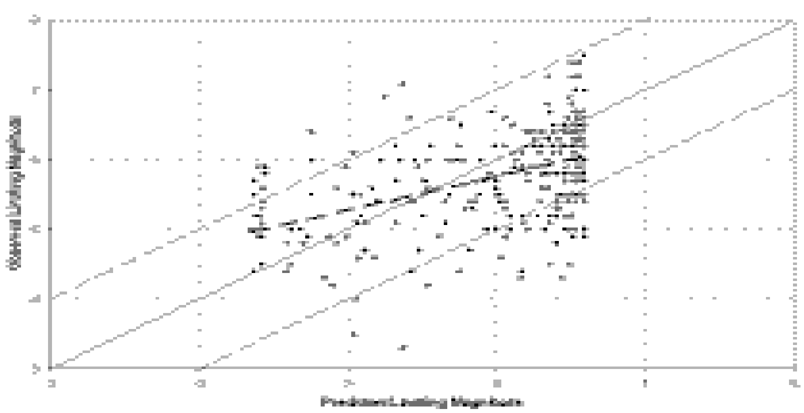

Figure 3. Plot of predicted vs. observed limiting magnitude for observations near sunspot maximum. The solid line represents observed=predicted, the dashed fine lines show one magnitude lower and higher than predicted, and the bold dashed line is the best fit linear regression of the data.

of protecting night sky visibility. When the image generated by the model is imported into a geographic information system such as ArcInfo, and the park boundaries superimposed, a simple intersection of the two themes yields data on the relative proportion of each park that falls within each of the Schaaf scale classes. Figures 4 through 8 show selected regions of the USA (in a negative image for clarity) with NPS areas superimposed upon the light pollution model. The state boundaries are also added, and the maps are produced in Lambert's Conformal Conic Projection.

Examination of these maps reveals that, as of 1990, large areas of the West were predicted to still possess Schaaf class 7 (pristine) skies, while such sites were very rarely east of the Mississippi River. Large areas of class 7 skies are seen in Nevada, Montana, North Dakota, eastern Oregon, southeastern Utah, northern Arizona, western Texas, and Wyoming. These regions were far enough from large urban centers that the influence of light pollution was minimal. Several large and well-known national parks fall within these areas, including Glacier, Yellowstone, Canyonlands, Grand Canyon, and Death Valley.

The GIS analysis produced a table of park areas showing what percentage of the area within each park

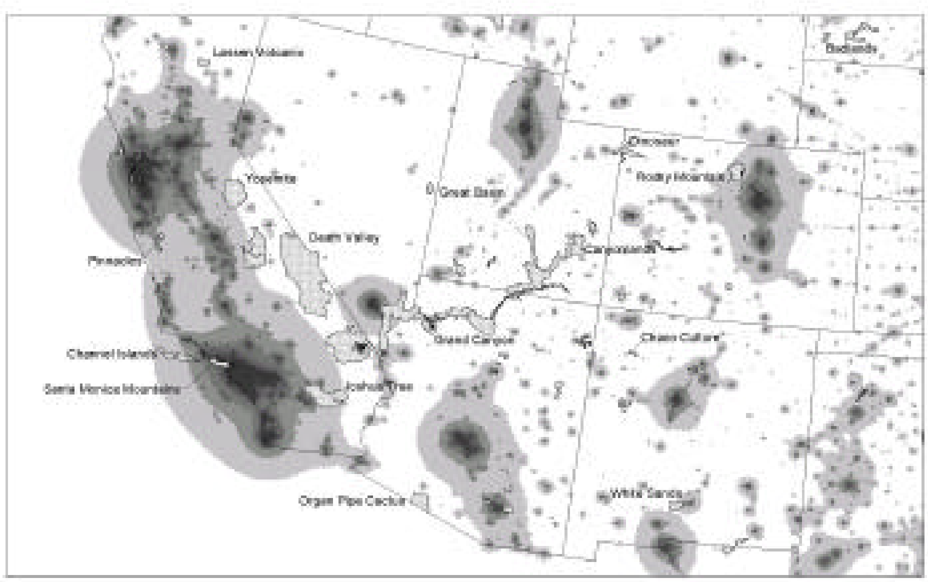

Figure 4. Light pollution and national parks in the Southwest.

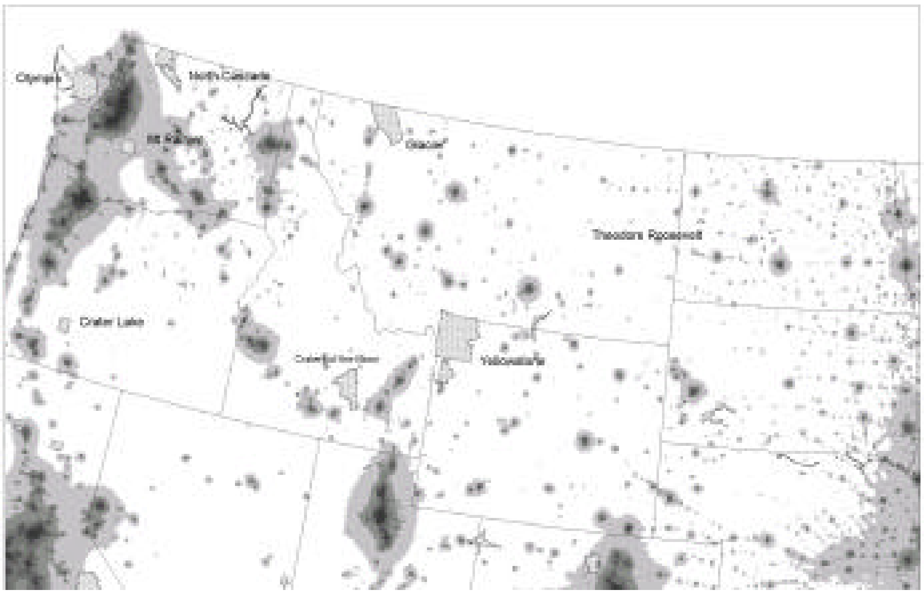

Figure 5. Light pollution and national parks in the Northwest.

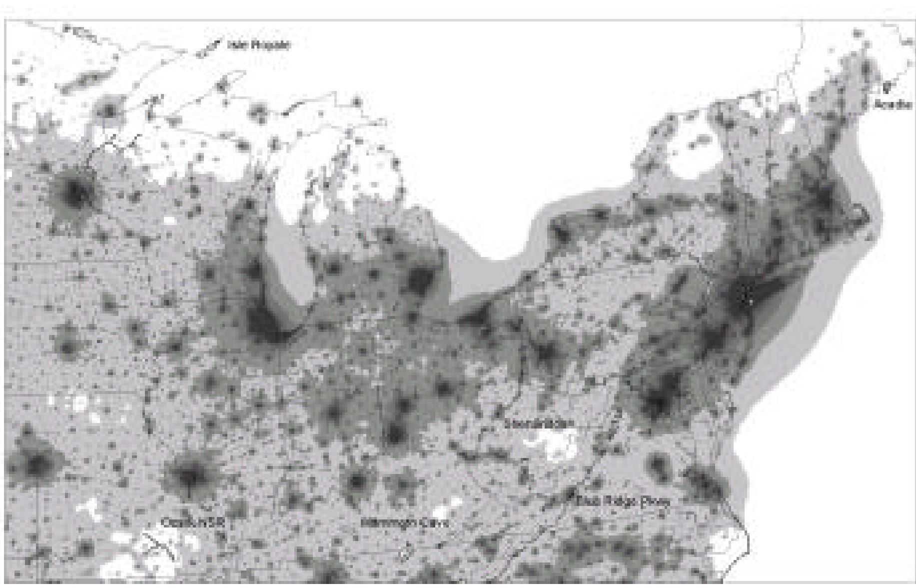

Figure 6. Light pollution and national parks in the Northeast.

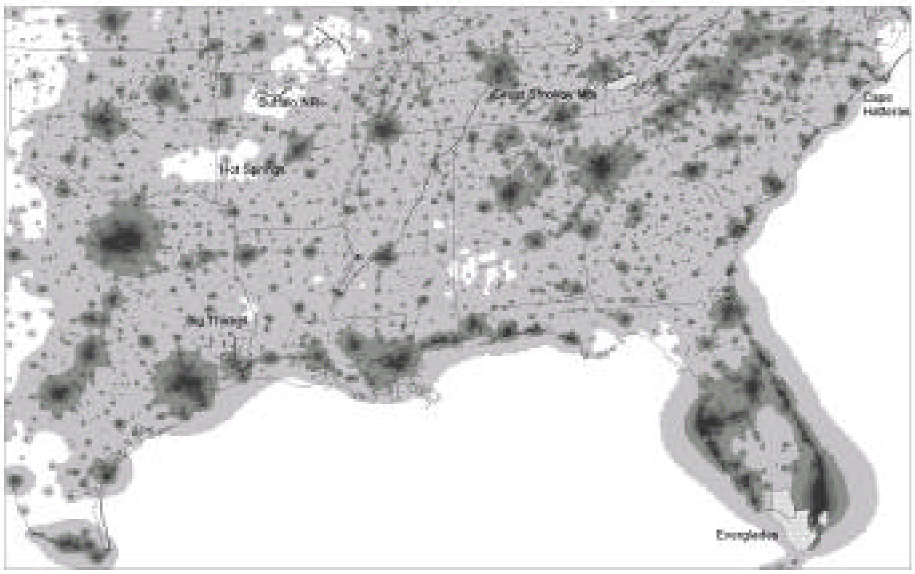

Figure 7. Light pollution and national parks in the Southeast.

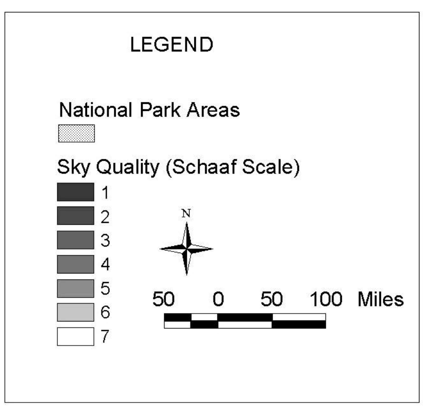

Figure 8. Legend for Figures 4-7.

fell within each of the Schaaf classes. Also, a mean Schaaf class was computed, and the total acreage of each park was calculated (Table 2). Not all park areas are shown: many were edited out for brevity, and the authors apologize in advance if the reader's favorite park was left out. The table is ordered first from darkest to brightest mean Schaaf class, then alphabetically by park name for parks with identical means. Note that

Table 2. Analysis of sky quality at selected NPS areas.

Park name	*Total acres*	*Mean Schaaf class*	*Percentage of land area within each Schaaf class*						
			1	*2*	*3*	*4*	*5*	*6*	*7*
Badlands NP	241,284	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Big Bend NP	827,169	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Canyonlands NP	331,342	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Capitol Reef NP	241,505	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Carlsbad Caverns NP	46,921	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Chaco Culture NHP	34,504	7.00	0.0	0.0	0.0	0.0	0.0	0.5	99.5
Chiricahua NM	12,225	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Crater Lake NP	180,631	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Craters of the Moon NM	750,312	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Devils Tower NM	1,341	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Death Valley NP	3,370,969	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Dinosaur NM	208,650	7.00	0.0	0.0	0.0	0.0	0.0	0.1	99.9
Dry Tortugas NP	72,382	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Gila Cliff Dwellings NM	526	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Glacier NP	1,026,615	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Great Basin NP	76,349	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Great Sand Dunes NP	38,202	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Guadalupe Mountains NP	88,254	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Hovenweep NM	797	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Isle Royale NP	143,269	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Lava Beds NM	46,004	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Lassen Volcanic NP	106,239	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Natural Bridges NM	7,324	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Navajo NMON	597	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
North Cascades NP	510,531	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Organ Pipe Cactus NM	331,119	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Petrified Forest NP	94,430	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Rainbow Bridge NM	161	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Theodore Roosevelt NP	71,048	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Voyageurs NP	208,263	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Wupatki NM	36,164	7.00	0.0	0.0	0.0	0.0	0.0	0.0	100.0
Grand Teton NP	308,640	6.99	0.0	0.0	0.0	0.0	0.0	0.5	99.5
Yellowstone NP	2,197,269	6.99	0.0	0.0	0.0	0.0	0.2	0.3	99.5
Grand Canyon NP	1,197,475	6.98	0.0	0.0	0.0	0.0	0.5	1.2	98.3
Glen Canyon NRA	1,238,424	6.97	0.0	0.0	0.0	0.0	0.5	2.0	97.5
Apostle Islands NL	42,170	6.96	0.0	0.0	0.0	0.0	0.0	3.6	96.4

Table 2. Analysis of sky quality at selected NPS areas (continued)

Bryce Canyon NP	35,761	6.94	0.0	0.0	0.0	0.0	0.0	6.3	93.8
Kings Canyon NP	454,632	6.94	0.0	0.0	0.0	0.0	0.0	5.9	94.1
Zion NP	146,400	6.94	0.0	0.0	0.0	0.0	0.0	5.7	94.4
Ozark NSR	81,346	6.90	0.0	0.0	0.0	0.0	0.1	9.5	90.5
Nez Perce NHP	2,309	6.88	0.0	0.0	0.0	0.0	3.4	5.3	91.3
Buffalo NR	94,619	6.84	0.0	0.0	0.0	0.0	0.0	15.7	84.3
Arches NP	75,738	6.82	0.0	0.0	0.0	0.0	1.8	14.9	83.3
Wind Cave NP	28,134	6.81	0.0	0.0	0.0	0.0	0.0	19.1	81.0
Cape Hatteras NS	30,873	6.79	0.0	0.0	0.0	0.0	0.9	19.1	80.0
Canyon de Chelly NM	91,78	6.77	0.0	0.0	0.0	0.0	5.6	11.6	82.8
Redwood NP	114,563	6.77	0.0	0.0	0.0	0.0	2.9	17.2	79.9
Mesa Verde NP	52,692	6.72	0.0	0.0	0.0	0.0	0.0	28.5	71.5
Acadia NP	38,695	6.70	0.0	0.0	0.0	0.4	0.0	29.0	70.6
Yosemite NP	740,969	6.67	0.0	0.0	0.0	0.0	0.0	32.9	67.1
White Sands NM	145,216	6.63	0.0	0.0	0.0	0.0	0.6	36.2	63.2
Niobrara/Missouri NRs	102,034	6.49	0.0	0.0	0.0	0.0	5.7	39.2	55.1
Sequoia NP	401,384	6.48	0.0	0.0	0.0	0.0	0.0	52.1	47.9
Olympic NP	926,349	6.45	0.0	0.0	0.0	0.0	0.0	54.7	45.3
Lake Mead NRA	1,255,884	6.30	0.0	0.0	0.0	1.2	6.4	53.6	38.8
Coronado NMem	4,895	6.00	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Mount Rainier NP	237,165	6.00	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Mount Rushmore NMem	1,305	6.00	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Sunset Crater Volcano NM	3,021	6.00	0.0	0.0	0.0	0.0	0.0	100.0	0.0
Mammoth Cave NP	50,356	5.99	0.0	0.0	0.0	0.0	0.6	99.4	0.0
Pinnacles NM	26,905	5.99	0.0	0.0	0.0	0.0	1.0	99.1	0.0
Rocky Mountain NP	264,124	5.98	0.0	0.0	0.0	0.8	0.3	98.9	0.0
Assateague Island NS	55,717	5.95	0.0	0.0	0.0	2.0	1.1	96.9	0.0
Bandelier NM	32,660	5.94	0.0	0.0	0.0	0.3	5.2	94.5	0.0
Great Smoky Mountains NP	514,688	5.94	0.0	0.0	0.0	1.0	3.9	95.1	0.0
Big Cypress NPres	758,335	5.85	0.0	0.0	0.0	0.0	14.6	85.4	0.0
Big Thicket NPres	89,793	5.85	0.0	0.0	0.0	2.6	9.8	87.6	0.0
Joshua Tree NP	790,699	5.84	0.0	0.0	0.6	0.2	22.2	68.2	8.8
Shenandoah NP	191,362	5.84	0.0	0.0	0.2	1.7	11.9	86.2	0.0
Channel Islands NP	242,284	5.82	0.0	0.0	0.0	0.0	18.4	81.6	0.0
Tallgrass Prairie NPres	10,762	5.80	0.0	0.0	0.0	0.0	20.1	79.9	0.0
New River Gorge NR	61,009	5.72	0.0	0.0	0.3	3.3	20.0	76.4	0.0

Table 2. Analysis of sky quality at selected NPS areas (continued)

Saint Croix NSR	97,938	5.71	0.0	2.8	9.2	8.5	10.7	31.6	37.2
Everglades NP	1,606,717	5.69	0.0	0.0	0.5	4.7	20.5	74.3	0.0
Blue Ridge Pkwy	89,722	5.65	0.2	2.4	2.9	2.9	10.4	81.2	0.0
Natchez Trace Pkwy	45,681	5.55	0.0	2.6	3.4	5.9	12.7	75.4	0.0
Upper Delaware S&RR	37,454	5.52	0.0	0.0	0.0	1.2	45.8	53.0	0.0
Cape Cod NS	40,202	5.33	0.0	0.0	0.0	12.2	42.8	45.0	0.0
Chickasaw NRA	9,938	5.32	0.0	0.0	11.7	1.3	30.0	57.0	0.0
Saguaro NP	93,733	5.07	0.0	0.0	1.8	11.4	64.9	21.9	0.0
Little River Canyon NPres	13,613	5.05	0.0	0.0	0.0	15.8	63.5	20.8	0.0
Colorado NM	20,193	4.98	0.0	0.0	8.8	8.3	58.7	24.2	0.0
Gulf Islands NS	121,888	4.77	4.5	0.4	13.4	9.3	39.7	32.7	0.0
Delaware Water Gap NRA	67,990	4.71	0.0	2.1	0.0	23.0	74.8	0.0	0.0
Point Reyes NS	66,199	4.59	0.0	0.0	6.6	28.0	65.5	0.0	0.0
Scotts Bluff NM	3,206	4.57	0.0	0.0	21.3	0.0	78.7	0.0	0.0
Gettysburg NMP	5,852	4.38	0.0	0.0	22.6	17.2	60.2	0.0	0.0
Harpers Ferry NHP	2,291	4.07	0.0	0.0	0.0	93.4	6.6	0.0	0.0
Pipestone NM	281	4.00	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Timpanogos Cave NM	245	4.00	0.0	0.0	0.0	100.0	0.0	0.0	0.0
Hot Springs NP	5,701	3.58	0.0	11.9	25.8	54.7	7.7	0.0	0.0
Biscayne NP	183,189	3.43	9.8	12.3	22.4	35.5	19.9	0.0	0.0
Cabrillo NM	138	3.00	0.0	0.0	100.0	0.0	0.0	0.0	0.0
Fort Sumter NM	200	2.95	0.0	4.5	95.5	0.0	0.0	0.0	0.0
Chattahoochee River NRA	8,667	2.93	5.2	40.4	24.5	16.3	13.7	0.0	0.0
Petroglyph NM	7,156	2.88	0.0	17.4	77.6	5.0	0.0	0.0	0.0
Chickamauga & Chatta-nooga NMP	8,181	2.80	0.2	28.0	63.4	8.3	0.0	0.0	0.0
Indiana Dunes NL	13,648	2.69	26.0	10.9	31.4	31.7	0.0	0.0	0.0
Jean Lafitte NHP/Pres	18,855	2.53	17.1	28.7	38.3	15.9	0.0	0.0	0.0
Santa Monica Mountains NRA	152,359	2.27	23.4	33.4	36.5	6.7	0.0	0.0	0.0
Cuyahoga Valley NP	32,211	2.22	11.6	54.7	33.7	0.0	0.0	0.0	0.0
Golden Gate NRA	76,080	2.10	55.4	11.6	5.8	22.1	5.1	0.0	0.0
Valley Forge NHP	3,453	2.00	0.0	100.0	0.0	0.0	0.0	0.0	0.0
National Capital Parks–East	7,440	1.56	43.5	56.5	0.0	0.0	0.0	0.0	0.0
Boston Harbor Islands NRA	1,575	1.03	97.2	2.8	0.0	0.0	0.0	0.0	0.0
Gateway NRA	26,704	1.00	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Independence NHP	51	1.00	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Muir Woods NM	567	1.00	100.0	0.0	0.0	0.0	0.0	0.0	0.0

the stated acreage may vary by as much as 2-3% from the true acreage because of the scale of the park boundary data used for the analysis.

Discussion

There appear to have been many park areas that still possessed pristine (mean Schaaf class 7.00) skies in 1990, according to this model. However, as seen in a previous section, observers have typically reported limiting magnitudes lower than those predicted for such areas, possibly indicating brighter-than-predicted sky quality (see Figure 3). Recent (2001) observations by Dan Duriscoe and Chadwick A. Moore at Death Valley National Park have shown that while the zenithal limiting magnitude may still be "pristine" (6.7 or better), a significant light dome from the city of Las Vegas, Nevada, is now apparent from most of the southeastern part of the park. Rapidly growing cities such as Las Vegas may now be significantly degrading the night sky as it appears from areas that had pristine viewing conditions just eleven years ago. Also, the city of Las Vegas is known to utilize bright advertising lights in great numbers and output. Therefore, the constant used in the model for in equation (3) may be larger than 11,300,000 for this city. The combination of a rapidly growing population and high light output per capita could result in much greater and longer-reaching light pollution than the model predicts. When the 2000 census data are readily available, the model can utilize the updated information and the predicted light pollution distribution should reflect changes in increased population and population migrations over the ten-year period.

Many "wild" national park areas are surrounded by or in close proximity to large urban centers, leading to a degradation of the view of the night sky. Examples are Great Smoky Mountains (mean Schaaf class 5.94) and Saguaro (5.06). Other park areas are very remote from large cities, but a small city is close by, such as Scotts Bluff (4.57).

Management Implications

This model may be used to predict the effect of future population growth on light pollution, thereby identifying future threats to night sky resources in national parks that are now relatively pristine. Verifying the model with actual observations should continue to lead to refinements of the "per capita" constant. Park areas that are both remote from large urban centers and are primarily wilderness parks should be identified as candidates for dark sky preserves. The declaration of this type of status, even if only local or informal, could lead to increased awareness and reduced light outputs by residents and businesses of local small communities. The managers of park lands, especially "dark sky parks," should make every effort to reduce light pollution from in-park facilities and concession activities, setting the very best example possible for their neighbors.

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