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Spatial-temporal expansion and determinants of light pollution in India's riparian habitats

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ABSTRACT

As the world embraced Artificial Light at Night (ALAN) and its numerous benefits, the transforming nocturnal environment witnessed the negative impacts of this contaminant of emerging concern, and its consequent Light Pollution, on the fitness and populations of numerous organisms. Over the decades, India's unbridled population growth and rapid urbanization have accelerated the use of ALAN yet research on light pollution, in India, as a potential biodiversity threat remains almost untapped.

The present study utilized nighttime light data from the Visible and Infrared Imaging Radiation Suite Day-Night Band (VIIRS DNB) to investigate the spatio-temporal trends of ALAN across India's major river basins, emphasizing on critical riparian habitats. The study also aimed to identify the significant effects on night-time brightness in these habitats.

Our findings indicated the year, riparian fauna group and presence within and near protected areas as significant determinants of light pollution in the riparian habitats of species of conservation concern. Light pollution was observed to grow in these habitats from the year 2012 to 2020. Higher radiance, in general, were observed for habitats near conurbations, airports, ports and docks, petroleum refineries, thermal power plants, and nuclear power stations. Otter and Turtle habitats had higher night-time brightness than other groups.

The significant increase of ALAN within a span of eight years is concerning, particularly for the critically endangered gharial, which was observed to inhabit predominantly darker habitats.

This, along with the gaps in our knowledge regarding the effects of ALAN on these species, urgently warrants a better understanding of its effects in riparian ecosystems. We have highlighted research gaps on ALAN from India's perspective and suggest that national biodiversity programs should evaluate ALAN as a potential biodiversity threat to limit its expansion in critical riparian ecosystems.

1. Introduction

> "On a dark, sandy beach a turtle hatchling follows a shining dome of light into the ocean. Little does it know that the light that guides it isn't from the moon, and what it thinks is the ocean is in fact a busy highway. The glow of a faraway city leads the hatchling to its doom and the bright lights do not even blink".

The preceding quote is not far from reality; Artificial Light at Night (ALAN) leads numerous sea turtle hatchlings and seabird fledglings to their fate as prey or roadkill on about 22% of the world's coasts illuminated by artificial lights (Davies et al., 2014).

But its implications for life on Earth go far beyond that. ALAN impacts have been identified across all biodiversity levels including genotypes, communities, ecosystems, and landscapes and its ever-growing extent has exposed the biosphere around the world to Ecological Light Pollution (ELP, Longcore and Rich, 2004, Hölker et al., 2010). ALAN can directly affect the behavior, physiology, and distribution of organisms over a broad spectrum of taxa, indirectly cause mortality by disorientation and light entrapment, and affect community composition in multiple biomes (aerial, aquatic, and terrestrial) (Longcore and Rich,

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2004; Gaston et al., 2013; Cinzano and Falchi, 2014; Davies and Smyth, 2018; Hölker et al., 2021). Especially freshwater and riparian areas are expected to be heavily impacted by ALAN (Jechow and Hölker, 2019), because >50% of the world's population live within 3 km from a freshwater water body (Kummu et al., 2011). The growing evidence of negative impacts of ALAN on taxa living in such habitats includes primary producers, zooplankton, insects, amphibians, fish, birds, turtles, and seals (Table S1).

ALAN is now widespread across the globe, extending over almost half of the world's landmass (Kyba et al., 2017; Gaston et al., 2021) Closely intertwined with population growth, settlements, urbanization, and industrialization, ALAN's geographical expansion is inevitable given how the global built-up area has doubled in the past four decades (Estoque et al., 2021).

With its growing Gross Domestic Product, young demographic base, and increasing urbanization, India is among the fastest-growing economies in the world. By 2050, the population is projected to reach 1531.4 million people (United Nations, 2021) whereas the urban area expansion is projected to expand by 9–12% (Huang et al., 2019). However, from a biodiversity perspective, this growth success story accentuates the demand for closer insights. The rapid geographical expansion of urbanization in India has led to extensive land-use modifications, particularly in biodiversity-rich areas, thus jeopardizing national conservation strategies. Although habitats both on land and in water are losing biodiversity worldwide, the decline is more acute in freshwater habitats (Reid et al., 2019; Maasri et al., 2022). Thus, it must be assumed that the burgeoning population and unrestrained urbanization have exerted severe pressure on biodiversity and habitats in India, which translates to the ecological imbalance in the rapidly urbanizing riparian habitats. Rivers, closely associated with the population, its livelihoods, and culture, are expected to become predisposed to high nighttime brightness from growing urban settlements and industries (Jechow and Hölker, 2019).

India's river system of 14 major, 44 medium, and countless small rivers (Ayyappan et al., 2006) harbors a plethora of flora and fauna including fish, birds, reptiles, and mammals. The ever-increasing industrial and domestic lighting, highways, and streetlights are ubiquitous within the proximity of rivers and have led to an exponential increase in the use of ALAN across critical riparian habitats. ALAN can exert combined effects with other stressors (Miller et al., 2017) or even exacerbate their influence (Nguyen et al., 2020). Furthermore, it is commonly assumed that ALAN only directly affects the environment in proximity of well-lit urban areas, resulting in an underestimation of the threat it indirectly poses to important habitats in protected areas that are gradually growing brighter (Xu et al., 2019; Gaston et al., 2021). Indirect light pollution results from light that is deflected by scattering in the atmosphere and then appears as skyglow. Skyglow is visible over long distances and can result in night sky brightness hundreds of times higher than in nature (Jechow et al., 2020).

Despite the ever-increasing evidence against ALAN as an emerging biodiversity threat, it is given scant consideration in India (Kumar et al., 2019; Bedi et al., 2021). In addition, its influence on aquatic habitats is relatively less known (Davies et al., 2014; Jechow and Hölker, 2019), and the phenomenon is largely unexplored in the context of Indian riverine systems. To the best of our knowledge, no studies exist that assess the expansion of ALAN in critical Indian riparian habitats.

In light of these fundamental knowledge gaps, the present study attempts to understand the extent and trends of ALAN in critical riparian habitats of species of concern (those listed as threatened species in the IUCN Red List and associated species), to answer the following questions: (i) Are the major Indian River basins including the habitats of species of conservation significance exposed to light pollution? (ii) What have been the trends and intensity of ALAN in these habitats between 2012 and 2020? (iii) What are the significant determinants that expose riparian fauna to light pollution in India?

2. Material and methods

2.1. Night-time light data

The Average dataset from the Annual VNL V2 series of the Visible and Infrared Imaging Radiation Suite Day-Night Band (VIIRS DNB) of the Suomi National Polar-Orbiting Partnership satellite was acquired for the years 2012 and 2020 from Earth Observation Group (https://eogdata.mines.edu/products/vnl/). The sensor provides global calibrated nighttime radiance measurements in a spectral band of 500 to 900 nm, which is close to the visible band and at a spatial resolution of near 750 m (Miller et al., 2013; Kyba et al., 2015). The dataset discards sunlit, moonlit, and cloudy pixels, as well as outliers from biomass burning using the 12-month median values to obtain annual composite values with stable standard deviation and gives the average annual radiance in $nW/cm^2/sr$. The dataset was clipped to India's boundary for faster and more efficient data processing by the software used.

2.2. Species sighting and nesting data

Several species of waterbirds, aquatic reptiles such as crocodiles and turtles, and Asian otter species were selected for the study based on their priority status and available secondary data on their occurrence and nesting habits (Table S2). For the present study, 44 occurrence and nesting sites of riparian birds, 50 sites for gharial, 39 sites for turtles and 45 sites for otters were marked with the help of reference literature. In some locations, Mugger (*Crocodylus palustris* Lesson, 1831) was reported to occur in association with the gharial (*Gavialis gangeticus*, Gmelin 1789), though it was not one of the target species of the study. The locations of the nesting and occurrence sites were approximated to mark suitable points along rivers, streams and on sandbanks and sandbars where the exact coordinates were not available and only a general area was mentioned, the positions corrected to align with the natural riparian habitats of the species. Since this study principally focuses on mapping the change in radiance within the habitats of the selected species, no points were excluded as long as they occurred within the natural range of the species and in the expected habitat. Points were also classified according to their occurrence in or near protected areas, and in non-protected areas, using information from the data source or the base map.

2.3. Data analysis

The clipped nighttime light (NTL) data was classified according to the Brightness Index proposed by Bedi et al. (2021), and thus, three levels were assigned to light pollution following the same index. Radiance from 0 to 1.2 nW/cm2/sr indicate dark sky sites, 1.2–13.0 nW/cm2/sr indicates the range from the onset of light pollution to medium light pollution, and values above 13.0 nW/cm2/sr indicate high light pollution.

The line data for major river basins as classified by the Central Water Commission, Government of India was overlain on the raster layers containing the data on average annual radiance for 2012 and 2020. A buffer of 2 km was placed on the line data for the major river basins. The function "Zonal statistics" (QGIS Project, 2022a) was then performed by merging these buffers and the VIIRS-DNB data for 2012 and 2020, respectively. The mean, median, average, minimum and maximum values, along with the standard deviation for the radiance in the two years were obtained from this analysis.

For analysis of point data (individual occurrence and nesting locations), The radiance at each point in 2012 and 2020 was determined using the function "Sample raster values" (QGIS Project, 2022b) by overlaying the point data over the nighttime light data for the two years respectively.

Microsoft Excel and IBM SPSS Statistics for Windows, version 21 (*IBM Corp*, 2012) were used for analysing the data. First, descriptive statistics were performed on the data to observe the general trends of nighttime brightness in the riparian habitats. The radiance at the sites did not follow a normal distribution (Shapiro-Wilk normality test, $p < 0.01$). Generalized Linear Mixed Models (GLMM) were fitted in IBM SPSS Statistics for Windows, version 21 (*IBM Corp*, 2012) to investigate the determinants of radiance in riparian habitats, using an Inverse Gaussian distribution with identity function. The year, riparian fauna group (Birds, Gharial, Turtles and Otters) and the presence of the site within or near protected areas were treated as fixed effects and the sites nested within rivers were taken as the random effects. For the gharial, however, only the rivers were taken as the random factor, as the nested factors were redundant for the group. GLMM were fitted for the different riparian fauna groups as well, to determine significant effects for each. In each case, the models with the lowest AIC values were selected. Gamma distribution with identity function was used for Bird, Turtle, and Otter habitats, while an Inverse Gaussian distribution with identity function was found to be the best fit for the radiance in Gharial habitats.

3. Results

3.1. Geographical extent of ALAN across river basins of India

The highest mean radiance, in 2020, was found in the Sabarmati Basin followed by East-flowing rivers between Pennar and Kanyakumari, West flowing rivers between Tapi and Tadri, and Ganga Basin. The average radiance in the river basins was observed to increase 1.8-fold between 2012 and 2020, and ALAN surpassed the radiance of 1.2 nW/cm^2/sr, the threshold considered in this study (Fig. 1a,b and c). The details of night-time brightness along major river basins can be found in Table S3.

GLMM revealed a significant ($F = 181.288$, $p < 0.01$) effect of the year on the exposure of the river basins to light pollution, indicating a significant increase in light pollution in these basins (Fig. 1d), particularly within rapidly urbanizing river basins such as the Sabarmati and Ganga.

Natural gas refineries, thermal and atomic power stations, and residential complexes contributed to strong ALAN (> 13 nW/cm^2/sr) at various locations in the basins.

In the Ganga River Basin, from 2012 to 2020, the mean radiance increased 1.7 X within eight years. In 2020, the maximum radiance was observed near Panipat, a city within the Ganga River Basin known for having one of Southeast Asia's largest integrated petrochemical plants.

3.2. Spatial and temporal variability of ALAN in critical riparian habitats

Satellite night time imagery has immense scope in detecting human presence in comparison to daylight remote sensing. Built up features and other on-ground disturbances under dense canopy or in rural landscapes often go undetected in day time satellite imageries while they are well detected in night time images due to the stark contrast of lighted pixels against the dark background. Fig. S1(a) depicts the 2020 night time VIIRS DNB image of India. Fig. S1(b-e) visualises a comparison of various landscapes, urban and rural; protected and inhabited areas at various spatial scales. Interestingly these sites are also key riparian habitats, few of which have even reported nesting. The image also demonstrates how the sphere of influence ALAN exhibits, is proportional to its proximity to lighting, the intensity and the nature of the light source (clustered urban lighting or single high intensity lighting like a shipyard, petroleum exploratory).

The year of radiance observation, species groups (Waterbirds, Crocodiles, Turtles and Otters), and location within or near protected areas were observed to have significant ($p < 0.01$) effect on exposure of the sampled site to light pollution (Fig. 3(a) and 3(b)). These results are discussed in the subsequent sections. The details of night-time brightness in Indian riparian habitats are given in Table S4.

3.2.1. Waterbirds

In the present study, the average bird occurrence and nesting site was relatively free of light pollution Fig 2(a). However, the mean radiance crossed the threshold of 1.2 nW/cm^2/sr in 2020. The location with the maximum radiance was situated by the Mahanadi. Sites near conurbations such as cities and towns showed higher radiance in general. Interestingly, in 2012 the minimum radiance was observed along the Chambal River however, this value witnessed an approximately three-fold rise (2.8 x) within eight years. ALAN was also observed to increase tremendously in cities by the Ganges, and the radiance was observed to increase for most sites between 2012 and 2020.

A significant effect ($F = 38.867$, $p < 0.01$) of the year existed on the light pollution at the sites of waterbird occurrence and nesting (Fig. 3(a)). Since the average radiance has increased in eight years in waterbird habitats, it can be expected that the exposure to this stressor and the consequent risks to the species will only increase in the coming years. The effect of the random factor, the location of the sites along specific rivers was also found to be significant ($p < 0.01$).

3.2.2. Crocodiles

In the present study, the average crocodile occurrence site occurred in dark areas Fig. 2(b). Except for two sites in the Brahmaputra (3.2285 nW/cm^2/sr) and Chambal (1.2082 nW/cm^2/sr), all the habitats exhibited radiance below 1.2 nW/cm^2/sr for both the years. The mean radiance in the gharial habitats was observed to increase by 2.7 X in eight years.

Significant effect of the year was observed on light pollution in Gharial habitats ($F = 20.343$, $p < 0.01$) (Fig. 3(a)). The species also appears to prefer dark habitats, as is indicated by the low radiance at most sites and the insignificant ($p < 0.05$) effect of the rivers in which they occur on the exposure of the species to artificial illumination.

3.2.3. Freshwater turtles

In the present study, the average turtle occurrence and nesting site occurred in brightness higher than Dark Sky sites Fig. 2(c). The average radiance in turtle habitats increased 1.4 X within eight years.

A significant ($F = 43.415$, $p < 0.01$) effect of the year on light pollution in the turtle habitats was observed (Fig. 3(a)). The location of the sites within each river also had a significant ($p < 0.01$) effect on the exposure of turtle habitats to light pollution.

3.2.4. Otters

Generally, the otters, in the present study, occurred in areas brighter than Dark Sky areas Fig. 2(d). The average radiance increased 1.5 X in their habitats between 2012 and 2020.

A significant ($F = 33.386$, $p < 0.01$) effect of the year was observed on the radiance in otter habitats (Fig. 3(a)). The radiance was also significantly ($p < 0.01$) affected by the sites located in different rivers.

3.3. Spatial-temporal variability of ALAN in protected and non-protected areas

The location of the sites within or outside protected areas had a significant effect on the exposure of the site to light pollution ($F = 7.968$, $p = 0.05$). The sites outside protected areas showed radiance 1.4 X higher than sites within and near protected areas in 2012. The ratio decreased to 1.3 X in 2020, with the protected areas becoming more exposed to ALAN.

The temporal analysis, from 2012 to 2020, reveals an increase in mean radiance in protected and non-protected areas (Fig. 3(b)). The radiance in non-protected areas increased by 1.6 X and that in protected areas increased by 1.7 X in eight years.

The year had a significant ($F = 59.682$, $p < 0.01$) effect on the radiance in sites outside protected areas. The same significance of effect ($F = 163.097$, $p < 0.01$) was observed for sites within and near protected areas (Fig. 3(b)).

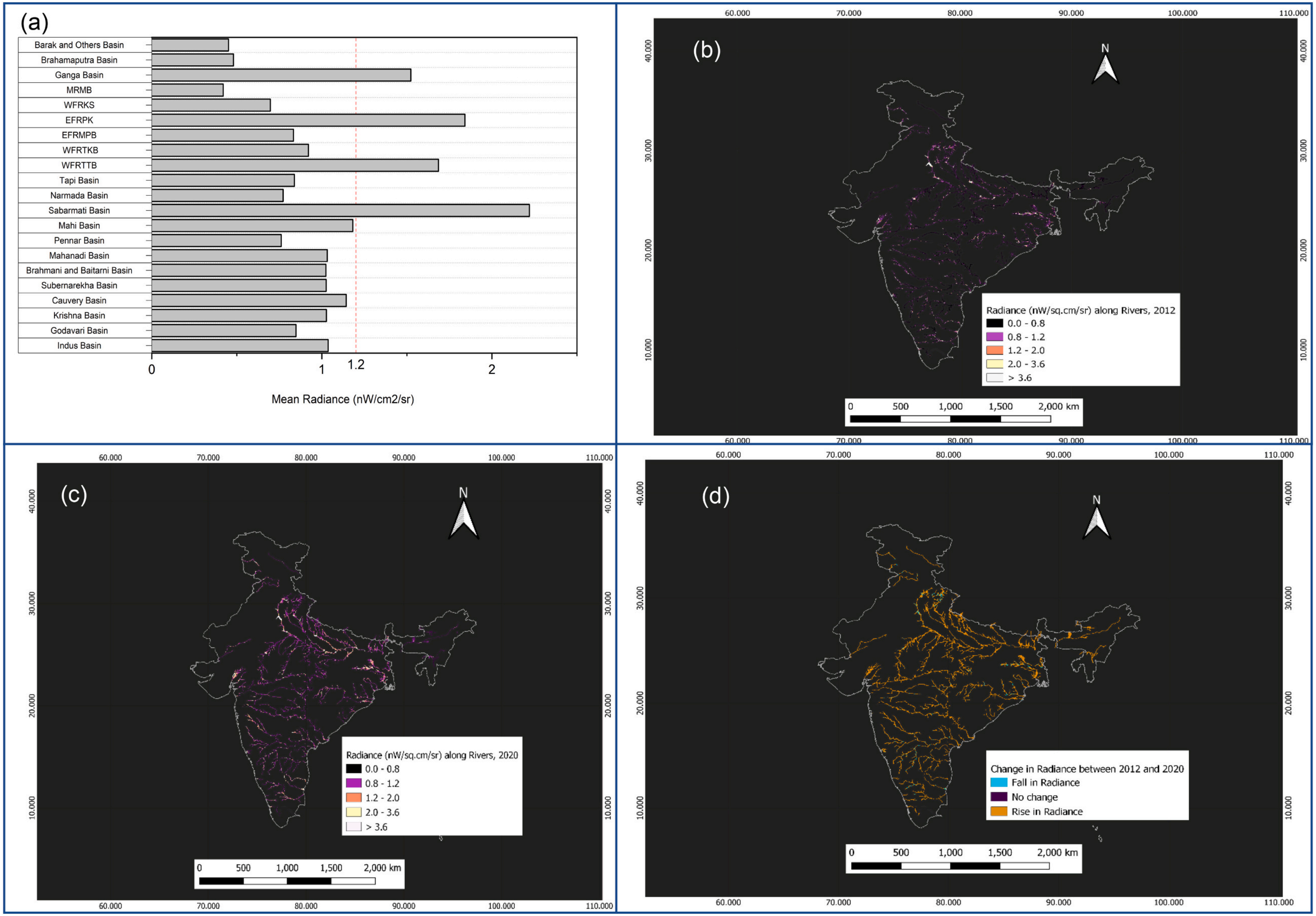

Fig. 1. (a) Mean values of average annual radiance for the year 2020 in different river basins of India. *The red dotted line represents the threshold (1.2 nW/cm^2/sr) for light pollution considered in the study.* (b) Mean values of average annual radiance in important river basins of India for the year 2012, (b) Mean values of average annual radiance in important river basins of India for the year 2020 (d) Change in radiance between year 2012 and 2020 (2 column-fitting image). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

WFRTTB: West-Flowing Rivers from Tapi to Tadri Basin; WFRTKB: West flowing rivers from Tadri to Kanyakumari Basin; EFRMPB: East flowing rivers between Mahanadi and Pennar Basin; EFRPK: East flowing rivers between Pennar and Kanyakumari; WFRKS: West flowing rivers of Kutch and Saurashtra; MRMB: Minor Rivers draining into Myanmar and Bangladesh.

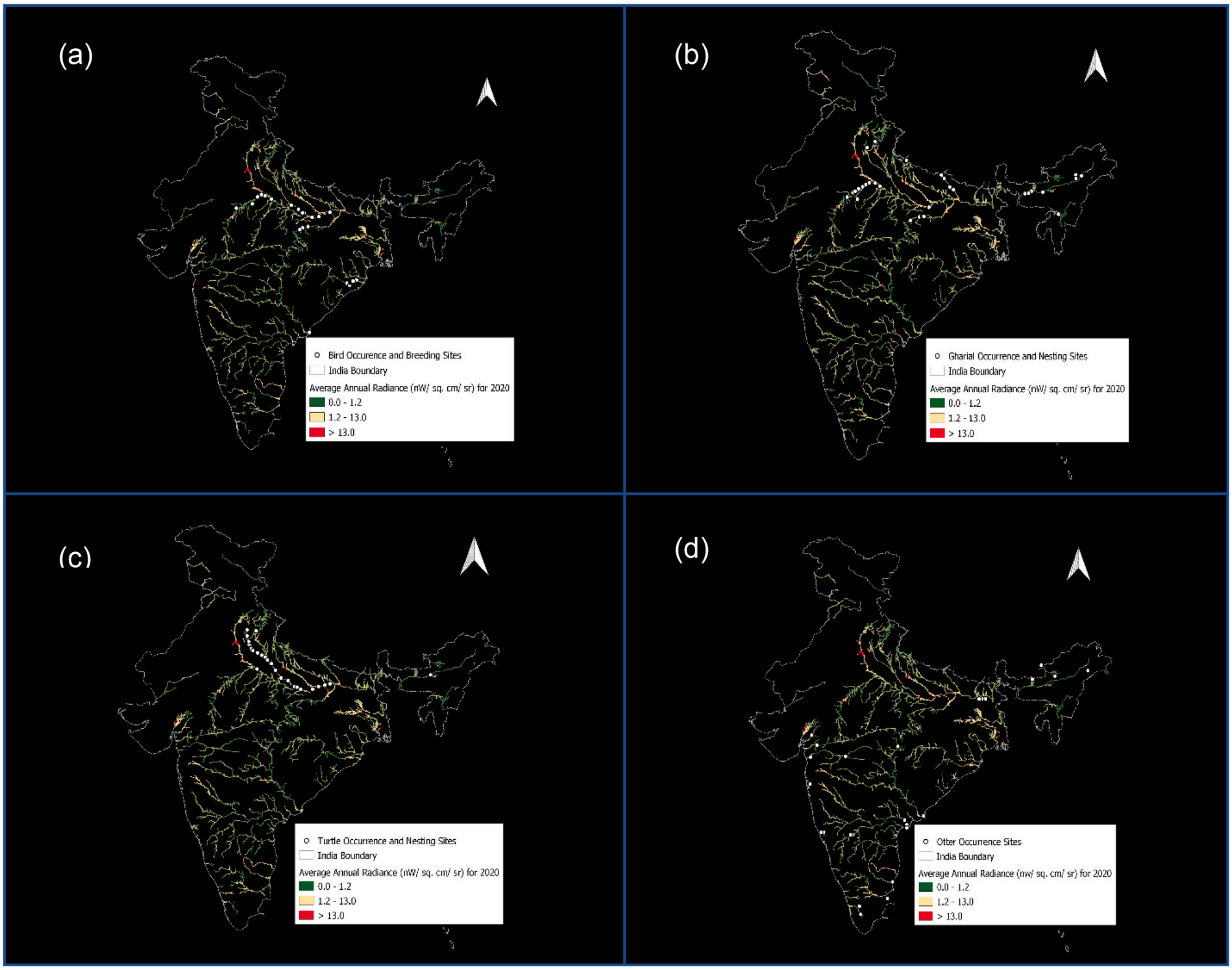

Fig. 2. Light Pollution in Riparian Habitats in India: (a) Waterbirds (b) Crocodiles (c) Freshwater turtles (d) Otters (2 column-fitting image).

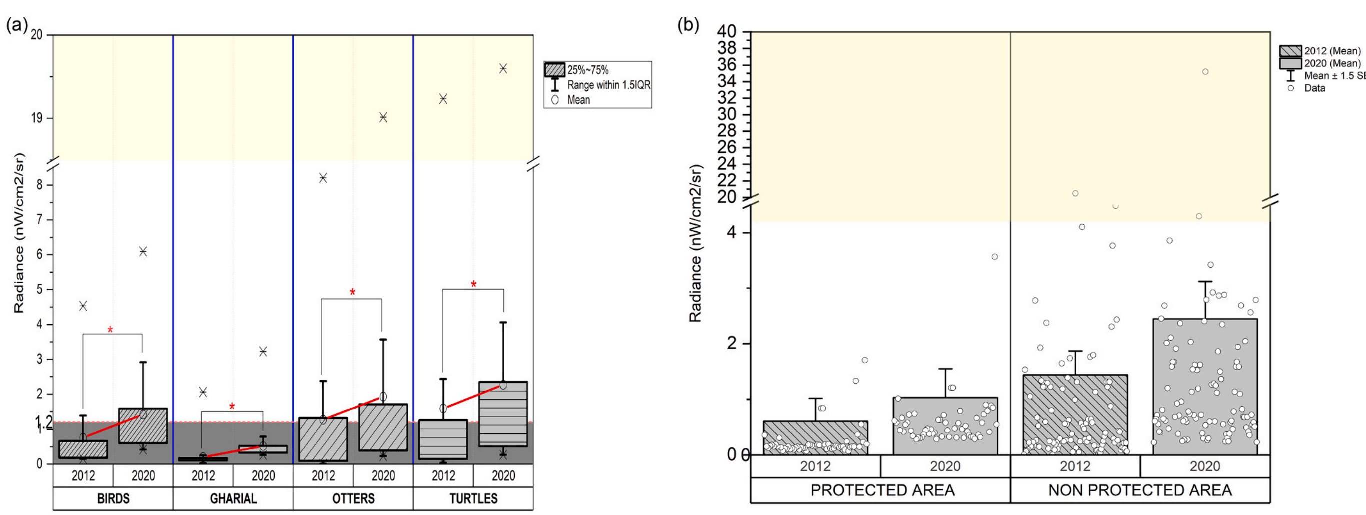

Fig. 3. Comparison of average annual radiance in 2012 and 2020 (a) for different riparian fauna groups, and (b) in protected and non-protected areas. The grey shaded portion represents radiance below the onset of light pollution, and the yellow shaded area represents high light pollution. The year, riparian fauna group and presence of the site with respect to protected areas had a significant ($p < 0.01$) effect on the night-time brightness at the sites. The year was a significant ($p < 0.01$) determinant of the brightness of the sites within and outside protected areas. (2 column-fitting image). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

Our results show a significant effect of year, species group and location within and near protected areas on the exposure of Indian riparian habitats to light pollution. The brightness has increased in the river basins and riparian habitats of India in the eight years between 2012 and 2022, which is alarming but not surprising, given the rapid urban, industrial, and economic growth of the country in the last few decades. The observance of growing radiance along India's river basins, from 2012 to 2020, could be attributed to increased residential complexes, major urban and economic hubs, airports, ports and docks, petroleum refineries, thermal power plants, and atomic power stations situated in and around the vicinity of these river basins. In the past three decades, a rapid increase in built area, and agriculture has also been observed along the major Indian river basins, including the Ganga river Basin (Shukla et al., 2018; Pani, 2020), Godavari(Koneti et al., 2018), Mahanadi (Das et al., 2019), Brahmaputra (Behera et al., 2018) and the Krishna river basin (Chanapathi and Thatikonda, 2020). These land-use changes risk exposing more naturally dark night landscapes to light pollution in the future, as artificial illumination from urban and industrial points, even distant ones, is of great importance, given how skyglow from these sources can exert its influence for tens to hundreds of kilometers (Davies and Smyth, 2018; Jechow et al., 2020). The rise in radiance along the Ganga Basin is exclusively concerning, as it supports rich biodiversity including many species of conservation significance such as the Indian Skimmer, Red-Crowned Roofed Turtle, the Gharial, and the Ganges River Dolphin.

The four groups of riparian fauna were also observed to be differentially affected by light pollution. The turtles and otters occurred in comparatively brighter sites as compared to birds and gharials. The details of the exposure of these groups to light pollution and the potential risks faced by them are discussed in subsequent paragraphs.

ALAN, identified as a threat to birds, affects their feeding and breeding behavior (de Molenaar et al., 2006; Robertson et al., 2010), and causes morbidity and mortality in seabirds (Montesdeoca et al., 2017). The heating effect of artificial lighting (Sturrock and Walker, 1934; Sayers and Duszkiewicz, 2002) can be considered as another threat to bird nests as the birds' behavior indicates efforts to lower the nest temperature (Das, 2015). Although the country is switching to more energy-efficient appliances such as LED lamps, part of the population still uses older light producing devices associated with higher heat generation. For example, 30% of households in the state of Gujarat, where the Sabarmati Basin is located, still used incandescent lamps in 2018 (Garg et al., 2021) From studies performed on seabirds such as petrels, it has been recommended that efforts be made to reduce light pollution to levels as low as possible within 3 km from petrel colonies. These studies recommend that colonies should not have radiance levels higher than 10 nW/cm^2/sr (Rodríguez et al., 2015a; Rodríguez et al., 2015b). Rebke et al. (2019) also recommended that blinking lights be used in coastal areas instead of continuous lights to limit the influence of artificial lights on nocturnally migrating birds. Although, in the present study, the maximum radiance levels at the riparian bird habitats were noted to be below 10 nW/cm2/sr for the years 2012 and 2020, the observed increasing trend in ALAN is a matter of concern and proactive measures need to be taken to ensure that this threshold is not crossed in the future.

Artificial illumination affects pigmentation, cardiac rate, and amphibious and predatory behaviors in crocodilians (Lang, 1976; Palmer and Palmer, 1994; Franklin and Seebacher, 2003; Merchant et al., 2018). Light pollution has been thus identified as a threat to protected crocodilian habitats (Kalwa and Opportunity, 2003). The gharial was observed to inhabit naturally darker areas than other groups, irrespective of the river in which the sites were located. The species' restriction to darker habitats and the lack of data on the effects of ALAN on crocodilians (Perry et al., 2008) could exacerbate the potential threats to the gharial.

Turtles are at risk from light pollution due to increasing industrialization (Kamrowski et al., 2012). The effects of ALAN are particularly well-studied in marine turtles. Skyglow is identified as a significant threat capable of causing disorientation in individuals >1.5 km away (Kamrowski et al., 2012). ALAN has been observed to negatively affect the nesting behavior of loggerhead turtles and increase the predation risk to hatchlings (Silva et al., 2017), which may be true for riparian species as well, but remains to be investigated. Assuming there is at least some similarity in the responses of marine and riparian turtles to ALAN, the present scenario of this stressor in India's turtle habitats is a matter of concern. The average values of radiance higher than 1.2 nW/cm^2/s, and the ever-increasing urbanization, industrialization, and land-use modifications in the proximity of important turtle habitats in the Ganga and Chambal raise concerns over the future of threatened turtle species in these rivers. The findings highlight the need for research focused on species' response to light. Pendoley and Kamrowski (2016) recommended a buffer radius of 1.5 km between sea turtle nesting sites and artificial lighting, with the light sources being shaded. Similar buffers must be explored for Indian riparian species.

The eyes in otters are adapted to low-light levels and are unaccustomed to rapidly changing light environments (Strobel et al., 2020). These piscivores are also known to utilize the difference between their visual abilities and those of their prey at twilight to hunt and forage (Carss, 1995). However, though these studies were from coastal regions, the same may also be true for riverine otters. It is possible that while artificial illumination may make it easier for them to visually identify and locate their prey, it may also make it easier for their prey to avoid being hunted. This, along with the phenomenon of positive and negative phototaxis in many fishes (Chen and Engert, 2014; Wei et al., 2019), might be the reason for the wide radiance range observed in the study. Despite the radiance being low for the points in the North-Eastern rivers, the greatest increase in radiance also occurred in the Brahmaputra River near Digboi oil fields. The modernization and up-gradation of petroleum and natural gas refineries could be the reason for the increasing illumination in this area.

The contribution of incessant illumination particularly in the protected areas associated with clusters of small sources such as mines, forest settlements, tourist lodges, and other anthropogenic settlements cannot be ignored (Koen et al., 2018; Gaston et al., 2021). Although most of the locations in protected areas had radiance corresponding to dark skies, the alarming rise in radiance at some locations along the Ganga, Tungabhadra, and Brahmaputra warrants concern and scientific attention. Some illegal activities in and around protected areas, such as sand mining, may contribute to small yet significant levels of artificial illumination. Oil refineries and associated structures within the vicinity of the protected areas, particularly in the Brahmaputra Basin, also extend their brightness into nearby areas. ALAN has been reported to be high along the periphery of protected areas, where it can act as a connectivity-weakening barrier between protected areas, and also as an ecological trap for species exhibiting positive phototaxis (Guetté et al., 2018), which may be lured outside these protected areas thus exposing themselves to life-threatening situations including vehicle collisions, electrocution and predation by domestic dogs (Chaves et al., 2022; Nuttall et al., 2022). In addition to the threats faced by various aquatic and terrestrial species in protected areas, the riverine habitat is also threatened by contaminants such as heavy metals, pesticides, pharmaceuticals, personal care products and endocrine-disrupting compounds that adversely affect the health and population dynamics of riverine organisms (Boral et al., 2020; Sah et al., 2020; Biswas and Vellanki, 2021)

4.1. Research gaps and recommendations

As urbanization expands, urban populations leave a disproportionately larger ecological footprint than rural populations. India is one of the fastest-growing economies in the world, and it is estimated that by

2050, approximately half of the country's population will be living in urban areas (Fig. 4a and b) (United Nations, 2021). With India's urbanization rate steadily increasing, the stress on the environment is also expected to rise. Given that urbanization and ALAN are inextricably linked, the present scenario suggests that ALAN can take two different turns; given the efforts made in the coming few years (Fig. 4c). The following paragraphs identify the research priorities and suggest some proactive measures that would be beneficial in bending the rising trend of ALAN in the coming years (Fig. 4c, represented as a dotted green line).

Because night-time satellite data are limited in spatial, spectral and temporal resolution we recommend regular monitoring of ALAN using both remotely sensed data and ground-based measurements in critical habitats and nesting sites of priority species in both protected areas and non-protected areas for biodiversity conservation. In addition, there is a great need for research studies on the impacts of ALAN across a wide variety of riparian fauna, particularly at-risk species, which will be critical in filling knowledge gaps and motivating policy-guided conservation actions (Hölker et al., 2021). Until baseline data and light pollution thresholds for endangered species are established in India, some international recommendations on species thresholds (Rodríguez et al., 2015b; Pendoley and Kamrowski, 2016; Rebke et al., 2019) and guidelines on containment of light pollution (Act on the Prevention of Light Pollution Due to Artificial Lighting 2012, Korea; Anti-Light Pollution and Energy Consumption Law 2013, France; Charter on External Lighting, Hong Kong Special Administrative Region, for example) may be considered as a proactive step to counteract the growth in ALAN (Zielinska-Dabkowska and Xavia, 2019). It should also be noted that as far as we know, no studies have been done to assess the impact of ALAN on the species considered in the present study, which alludes to the possibility that thresholds determined for other related species (mostly marine) may not work for the conservation of these species. This also highlights the need for research on the response of riparian species to ALAN and the effects of this stressor on their behavior and ecology. Sources of ALAN in their habitats also need to be identified, including in areas that may be quite distant from urban centres. It could also be worth implementing concepts for dark ecological networks consisting of core areas, corridors, and buffer zones to limit the effects of light pollution on biodiversity in river systems (Sordello et al., 2022).

However, it is critical to emphasize that such guidelines and policies are country-specific and may be difficult to implement, particularly in a megadiverse and developing country like India, where artificial lighting is intertwined with unrestrained population growth, socio-economic development, road safety. As a result, strategies for reducing ALAN that is publicly, economically, and environmentally acceptable on a national scale should be investigated. Finally, we strongly advocate the need for a government-backed community engagement program, particularly within the vicinity of critical riparian habitats. Community sensitization, such as building knowledge and awareness of the issue and encouraging the limited and modified use of artificial lighting (Gaston et al., 2012; Zielinska-Dabkowska and Xavia, 2019) will ensure positive and sustainable change.

5. Conclusion

The present study mapped the spatio-temporal expansion in ALAN for major river basins, including the habitats of species of conservation importance, for the years 2012 and 2020. The results indicate the exposure of important riparian habitats to ALAN, and highlight a rise in ALAN in major basins of India from the year 2012 to 2020. The observance of high ALAN, within eight years, particularly in biodiversity rich yet threatened riparian habitats including Ganga and Chambal is concerning. Residential complexes, large urban and commercial hubs, petroleum refineries, airports, ports and docks, thermal power plants, and atomic power stations were found as significant sources of ALAN in riparian environments. It is important to emphasize that biodiversity in these riparian habitats is already under severe stress due to various anthropogenic stressors including river fragmentation, chemical pollution and overexploitation of resources (Pellicer-Martínez and Martínez-Paz, 2016; Herrera-R et al., 2020; Seal et al., 2022) hence, the ecological impact of any new stressor such as ALAN may be even more pronounced.

An intriguing and concerning finding is the slow yet significant increase of ALAN, within the protected areas that warrant imperative measures. The case of the Gharial is especially alarming, as the species was generally found to occur in darker habitats and is therefore more susceptible to the risks posed by increasing nighttime brightness. Turtle and Otter habitats are also exposed to high levels of ALAN and warrant attention and proactive measures to control the spread of this stressor. Despite the well-documented, profound, and widespread impacts of ALAN, in particular, and ELP in general, the scant attention it receives from national environmental bodies and the scientific community in India is a matter of immense concern that needs to be addressed immediately.

The preliminary yet crucial finding of the present study brings much-needed attention to ALAN expansion in India. The paper also explores and suggests possible approaches for limiting ALAN's proliferation in India's riparian environments.

CRediT authorship contribution statement

Megha Khanduri: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Ruchika Sah:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Aishwarya Ramachandran:** Methodology, Validation. **Syed Ainul**

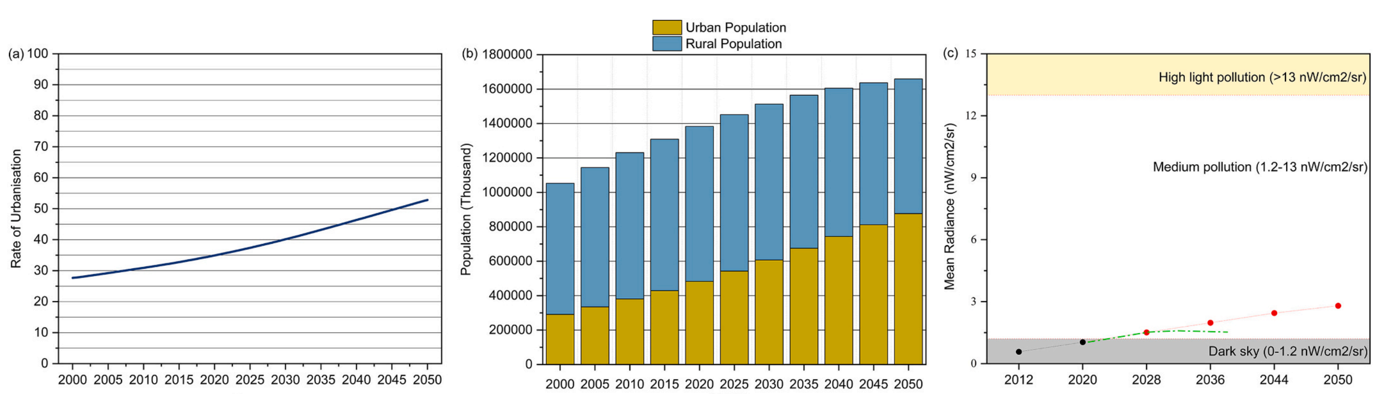

Fig. 4. (a) Rate of Urbanization, (b) Division of Urban and Rural population (c) Projected trends for ALAN* (2 column-fitting image). United Nations. Population division department of economic and social affairs united nations secretariat. Retrieved from: https://www.un.org/en/development/desa/population/publications/database/index.asp (2021). *Red circles represents the projected trends for ALAN.

Hussain: Resources, Supervision, Funding acquisition, Project administration, Writing – review & editing. **Ruchi Badola:** Resources, Supervision, Funding acquisition, Project administration, Writing – review & editing. **Ulrika Candolin:** Supervision, Writing – review & editing. **Franz Hölker:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2022.106952.

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