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Ecological light pollution An overview of impacts on the Wadden Sea

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Abstract

This report analyses the current state of light at night and the potential harmful ecological effects of which for the Wadden Sea, a UNESCO World Heritage site. Artificial light at night (ALAN) is shown to have increased in recent years for most parts of the Wadden Sea area. Five different types of ALAN sources are analysed and compared to the moon in regards to coastal water penetration. Potential consequences of ALAN are reviewed for migratory birds, sessile invertebrates (blue mussel & pacific oyster) and primary producers & invertebrate secondary producers. ALAN is shown to be able to be a serious stressor for marine and avian population levels and potentially the functioning of the Wadden Sea's ecosystem. ALAN alters biological rhythms, influencing marine and avian species on a sensory and physiological level and disrupts natural rhythms by creating eternal full moon scenarios. The current extent of ecological effects of ALAN is however, difficult to determine. As artificial sky brightness maps are subjected to assumptions and no models for (artificial) light propagating below salt-water surface are well developed. In the model reviewed in this report, it was concluded that the blue range of LED light sources is still present at 30m of coastal water depth in comparison to moonlight, where all is scattered away. Green wavelengths are also present in higher intensities at 30m depth compared to moonlight for certain ALAN sources. This report shows that ALAN is a cause for concern regarding the conservation of the Wadden Sea and its inhabitants. This report reviews options for minimising light pollution and emphasises the need for specifically developed research to properly determine the current ecological strain ALAN poses on the Wadden Sea.

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1. Introduction

1.1 The Wadden Sea

The Wadden Sea is the largest tidal flat and barrier system in the world and it hosts one of the last remaining large-scale intertidal ecosystems, where natural processes are for the majority undisturbed [available on: https://www.waddensea-worldheritage.org]. The Trilateral Wadden Sea Cooperation (TWSC) is a joint operation between Denmark, Germany and the Netherlands and has for the past four decades made an effort to protect and preserve the Wadden Sea area [waddensea-worldheritage.org]. In 2009 the Wadden Sea area was inscribed on the World Heritage List of UNESCO and in 2013 the TWSC admitted an extension of the Danish part of the Wadden Sea to be added. In 2014 the admission was approved, resulting in the Wadden Sea as whole to be officially a World Heritage site [waddensea-worldheritage.org]. The recognized world heritage region can be seen in the figure below.

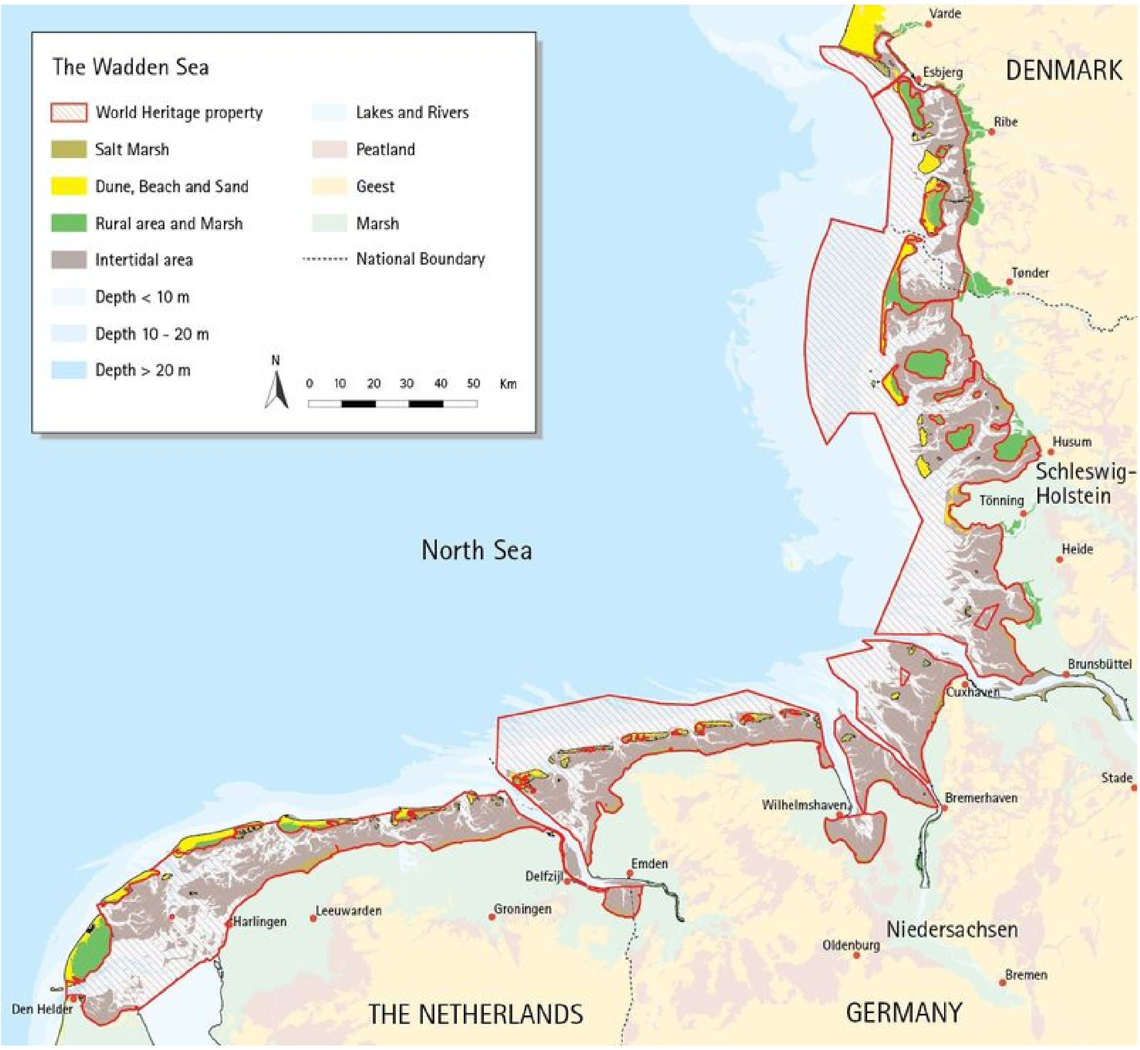


*Figure 1: The Wadden Sea World Heritage area [*available on: https://www.waddensea-worldheritage.org*]*

It is evident that the Wadden Sea is to be protected and preserved. With its presence of transitional habitats between sea, land and freshwater the production of biomass proves to be one of the highest in the world [available on: https://whc.unesco.org/en/list/1314/]. Because of this the Wadden Sea is regarded as one of the most important areas for staging (resting in large numbers), moulting (shedding of old feathers) and wintering of migratory birds. Among other resources the TWSC releases a yearly report on the status of migratory birds that make use of the African-Eurasian flyway regions. The presence of a big food supply and relatively low disturbance makes the Wadden Sea a key site for these flyways [whc.unesco.org/en/list/1314/]. Hence the Wadden Sea is important for ecosystems on a world-wide scale [whc.unesco.org/en/list/1314/].

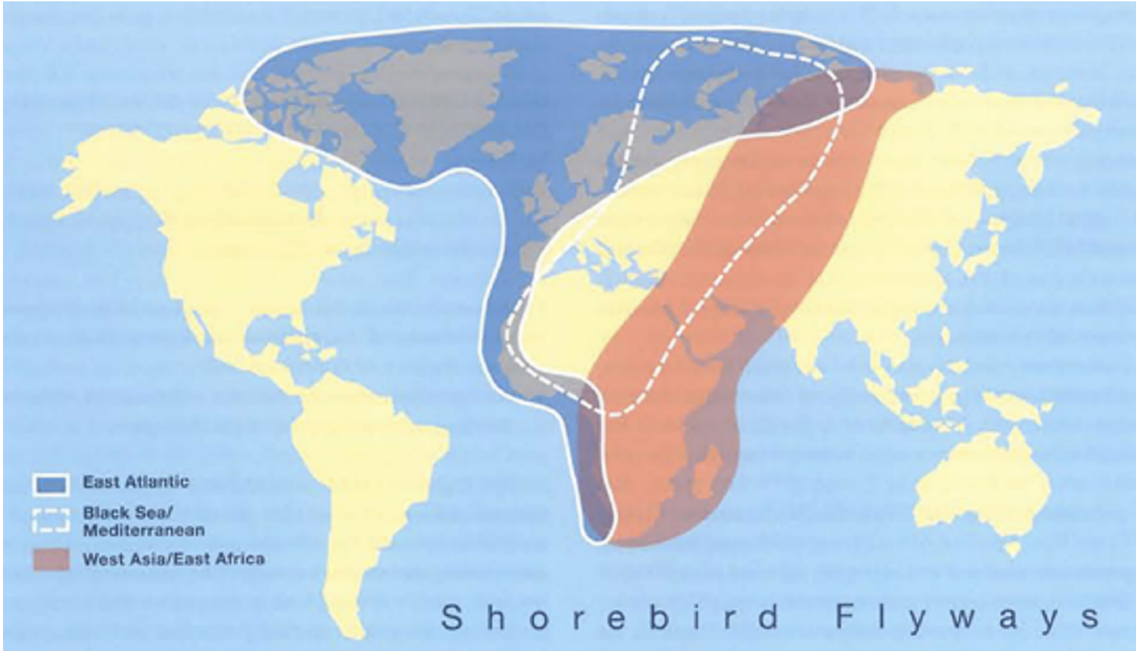


*Figure 2: Three regions that are regarded as flyways for migratory birds [*van Roomen 2020, et al*]*

While migratory birds are a key indicator for the importance of the preservation of the Wadden Sea, other factors are of great importance too. The availability and abundance of biomass is predominantly non-trivial for the ecosystem of the region. The variety, production and growth of this food source is the foundation for a rich and thriving food cycle in the transitional habitats, which houses a high diversity of terrestrial and aquatic species [www.waddensea-worldheritage.org]. One stressor for the preservation of the Wadden Sea is light at night. The Wadden Sea world heritage area borders human sites & settlements and humans have an apparent need to light up the night. Potentially disregarding the disruptive effects this has on the ecosystem, which is used to a constant day-night cycle [Gaston 2013, et al]. In this report the ecological effects of light at night on migratory birds and the biomass producing invertebrates primary producers, zooplankton, blue mussels and pacific oyster will be studied. All of which are intimately connected in the food web, so a stressor can have direct and indirect preservation consequences. Disruptive light at night is commonly known as light pollution. This report will analyse the known effects of light pollution on wildlife, whether and/or how the Wadden Sea is affected by light pollution and review conservation options regarding minimising light pollution.

1.2 ALAN

ALAN or Artificial Light At Night is a relatively recent cause of concern for conservation and preservation communities world-wide. It has been argued that natural illumination levels dictate the biological world [Gaston 2013, et al]. Species alter their physiological functions and behavioural patterns according to certain light levels [Health Council of the Netherlands 2000] and since for any given latitude the natural light fluctuations on Earth have been consistent for extremely long periods of time [Gaston 2013, et al], the increase of ALAN can have disruptive effects on various species and subsequently the balance of ecosystems [Davies 2013, et al; Gaston 2013, et al; Longcore 2004, et al; Lynn 2021, et al]. In the figure below, a conceptual map of the disruptive effects of ALAN is shown.

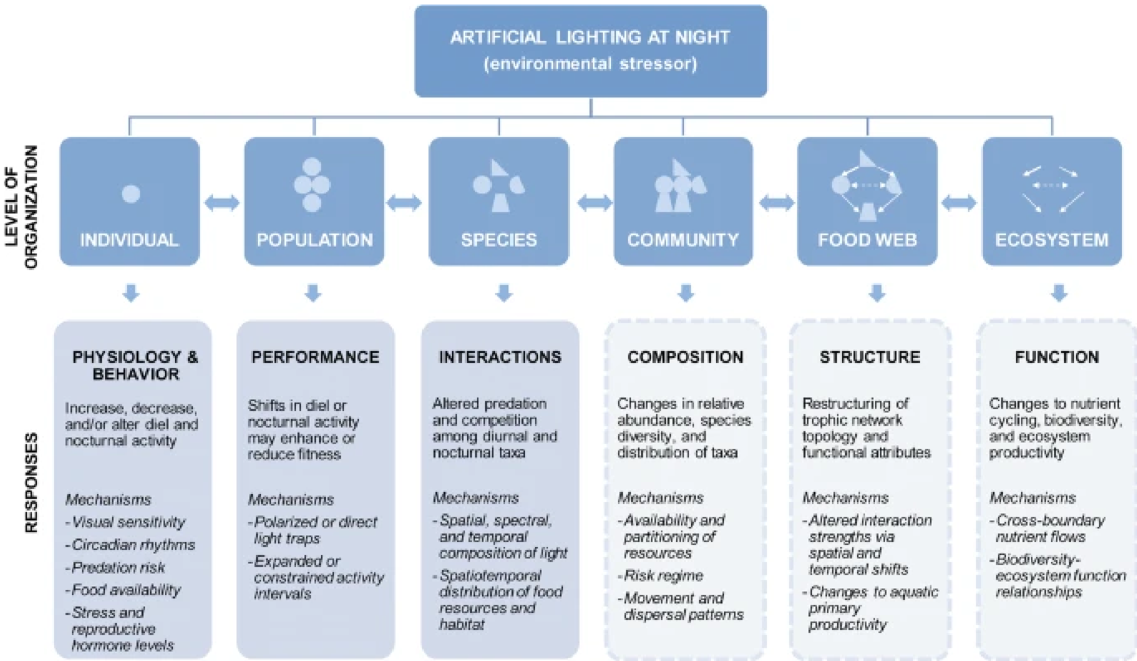


Figure 3: Conceptual map of responses to ALAN at different levels of biological organisation [Zapata 2018, et al]

In the recent decades various ecological implications of ALAN have been explored and because of this ALAN can also be referred to as "ecological light pollution" [Longcore 2004, et al]. Ecological light pollution stems from various different lighting typings such as direct glare, periodically or chronically increased illumination or unexpected fluctuations in lighting [Longcore 2004, et al]. Sources can include sky glow (the cumulative illuminating effect of a high number of light sources and most prominent in cities), street lanterns and vehicles, lit-up buildings and structures, fishing and undersea research vessels and lights on offshore oil platforms [Longcore 2004, et al]. Regarding the Wadden Sea, even though it is a regulated coastal area, it does suffer from light pollution sources originating from its surrounding terrestrial area, fishery activity and offshore oil platforms and windparks [Krop-Benesch 2022, et al]. Area's further removed from the coast should also not be neglected as research highlights that even low levels of light pollution at night can have a significant impact [Gaston 2013, et al].

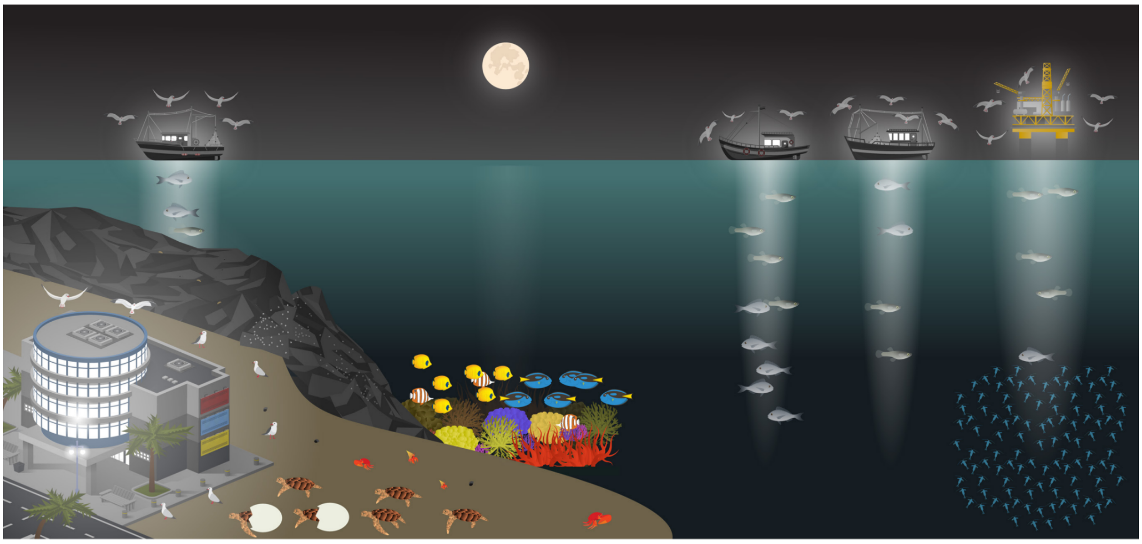


Figure 4: Conceptual coastal environment affected by ALAN [Marangoni 2022, et al]

It's important to note that artificial light differs from natural light in terms of its spectral composition. Sunlight and moonlight (reflected sunlight) contain wavelengths ranging from UV light, to all visible colours and infrared light. For moonlight the short-waved parts are reduced. Sources of ALAN do not emit all wavelengths and differ from each other. An overview of this is shown in the figure below.

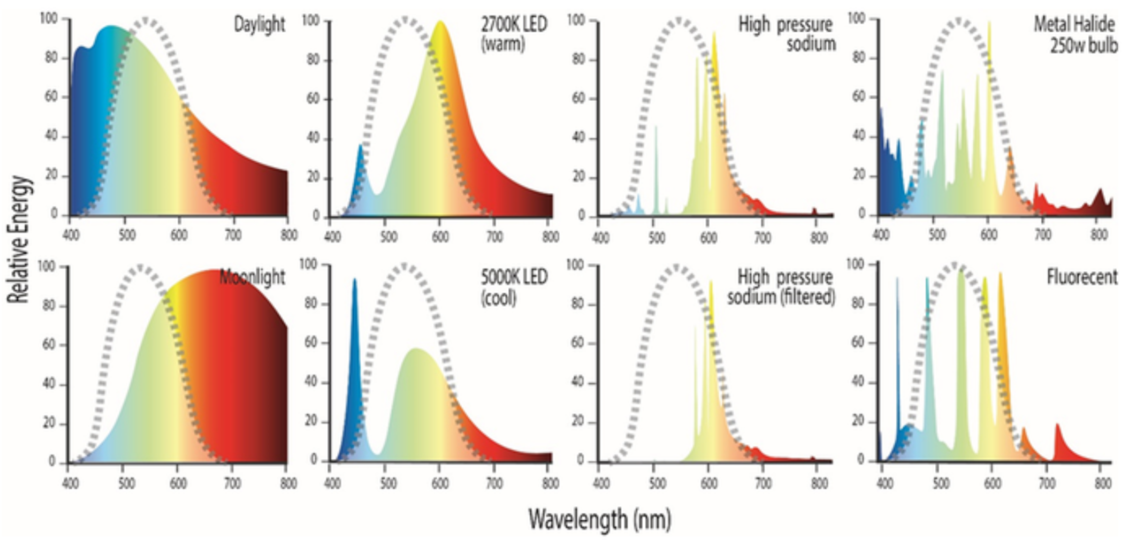


Figure 5: Spectral composition of natural light and common artificial light sources [Marangoni 2022, et al]

Different species react differently to various spectral compositions [Longcore 2018, et al]. While for most species ALAN related consequences are attributed to blue light wavelengths, there are findings of some species reacting stronger to long-waved (red) light [Chernetsov 2016, et al]. Important of note as well is that blue artificial light will in general penetrate deeper into water due to the different refraction indexes of the colours. Whether the light source is polarised or not is also of importance and it's been shown that for migratory birds natural polarised light is needed for the magnetic compass they make use of when migrating along their route [Mulheim 2016, et al].

1.3 Measurements of light pollution

Published results of light pollution can vary amongst research papers. For starters there is the issue of units. Most often in papers related to ecological effects of light the researchers measure or make use of illumination, which is the “amount” of light present per unit area. Most often their results are displayed in lux [Longcore 2004, et al]. However, lux emphasises the wavelength spectrum visible to the human eye. Because other species detect light differently including wavelengths not visible to the human eye, a portion of biologically relevant information would be ignored with the use of lux [Longcore 2004, et al]. Lux is a photometric unit which means each intensity is weighted according to a lumination function corresponding to human visual perception. Its corresponding radiometric unit, meaning each intensity is weighted equally over all wavelengths, is watt per square metre and describes irradiance. Global light pollution measurements analysed by NASA’s Black Marble project [worldview.earthdata.nasa.gov/], which makes use of data provided by open source satellite data such as from the VIIRS instrument [available on: https://eogdata.mines.edu/products/vnl/#annual_v2], provide their data in a form of irradiance. There is no single conversion factor between illuminance and irradiance, as for every wavelength there exists a different conversion factor and it is not possible to convert between the two unless one knows the spectral composition of the light source [available on: http://stjarnhimlen.se/comp/radfaq.html#7]. [Longcore 2018, et al] in an attempt to overcome this issue, has developed and proposed an index that identifies artificial light sources that minimise predicted ecological, physiological and astronomical effects. This way, new and developed lighting products can be tested and altered in a way such that it would minimise the effect the artificial light source has on a specific environment. This development is, however, pretty recent and has not been implemented in common ecological research regarding light pollution.

Another astronomical limitation to studies on light pollution is the fact that the only data available is either satellite data, which measures intensity in a vertical axis down, and SQM data, which are located on the ground and measure intensity in a vertical cone shape up. These two instruments can not measure and distinguish the spectral composition of the light, which as previously mentioned is of importance for ecological studies. Furthermore, marine and avian species in the Wadden Sea do not perceive light in a vertical axis, but perceive light coming from all angles and not only from direct sources [Katz 2016, et al]. A study on SQM measurements concluded that indeed satellite data does not accurately represent the exposure of artificial light to humans and other organisms [Katz 2016, et al]. This is because light emitted from an artificial source can get reflected and/or scattered when propagating through the atmosphere [Katz 2016, et al]. To properly quantify the light pollution for a given area a 3D mapping of propagated light needs to be developed. Taking into account the atmospheric scattering and reflection [Katz 2016, et al]. A conceptual diagram of why this is necessary is shown below.

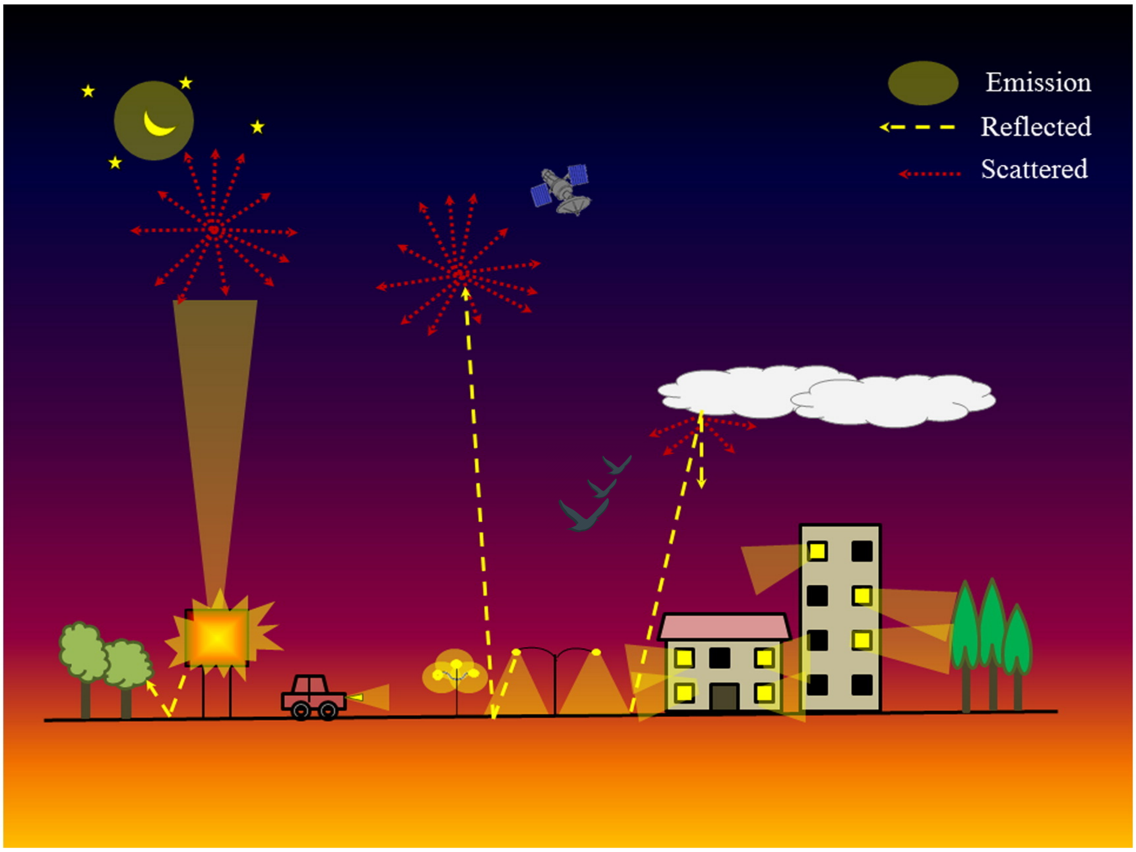


Figure 6: Conceptual diagram of light sources which get reflected and scattered in the atmosphere [Katz 2016, et al]

2. Method & Analysis

2.1 Mechanistic appraisal

For this study a variety of research papers were read, analysed, compared and reviewed. Given the wide range of units used in the literature and different reactions to various spectra of light for avian and marine species it was chosen to adhere to the proposed framework of [Gaston 2013, et al]. Classifying light either as a resource or as an information source.

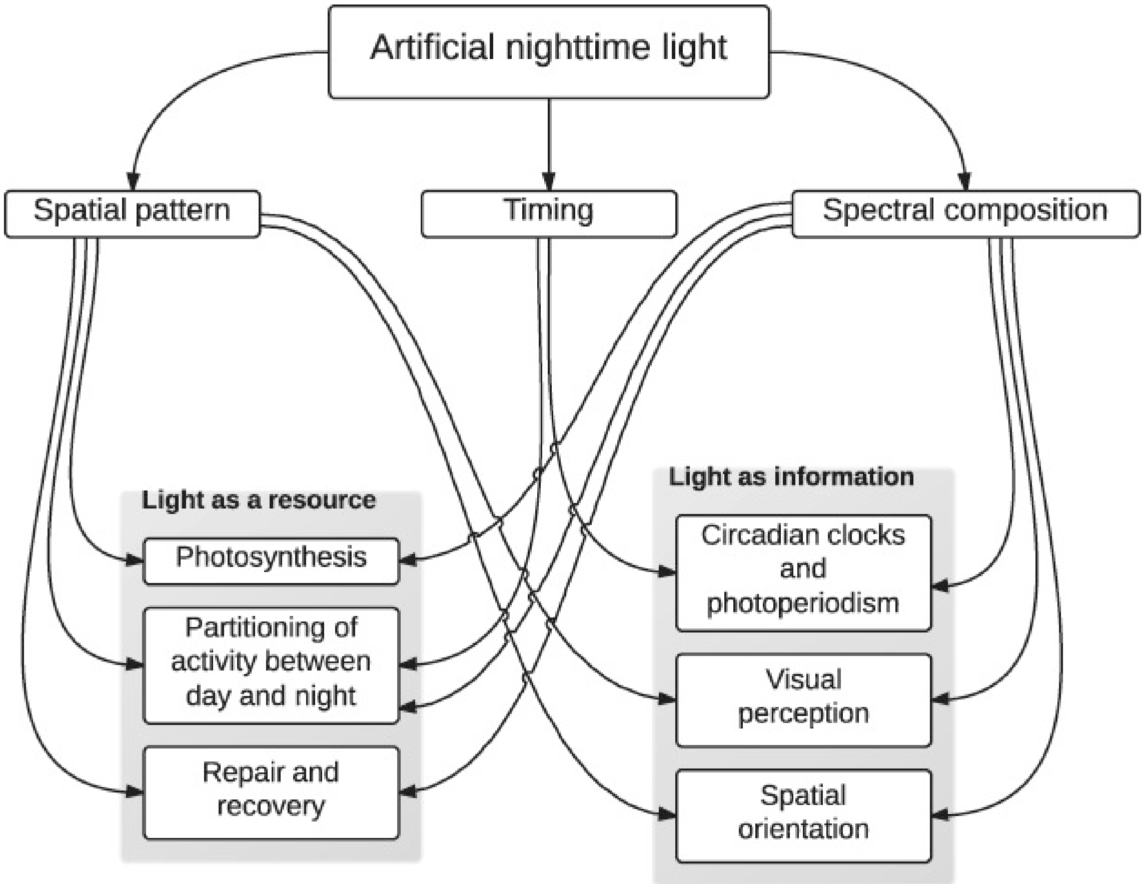


Figure 7: proposed framework to classify ALAN as either a resource or an information source [Gaston 2013, et al]

When researching the ecological impacts of ALAN on species they are either affected because the light they perceive disrupts their natural rhythm and/or perceive the light as a cue for certain natural processes (information). Or ALAN alters the species on a physiological level, inducing or reducing hormone production or extending activity time into the night (resource). This distinction proved to be a useful tool when analysing multiple papers regarding the ecological light pollution topic.
For effects of light pollution on known species, it was chosen to analyse effects on migratory birds, immovable invertebrates (animals lacking a backbone) and primary and invertebrate secondary producers. These effects were then tabelized and categorised adhering to the framework mentioned above.

2.2 VIIRS & SQM assessment

There are two astronomical measuring techniques to quantify the artificial sky brightness. Satellite imaging using the VIIRS instrument and Sky Quality Metres. The spectral response of these two techniques were acquired and correlated to the spectral compositions of some common artificial light sources and the moon in order to compare whether and which of the ALAN sources could be more disruptive. Such a correlation looks like the following when normalised:

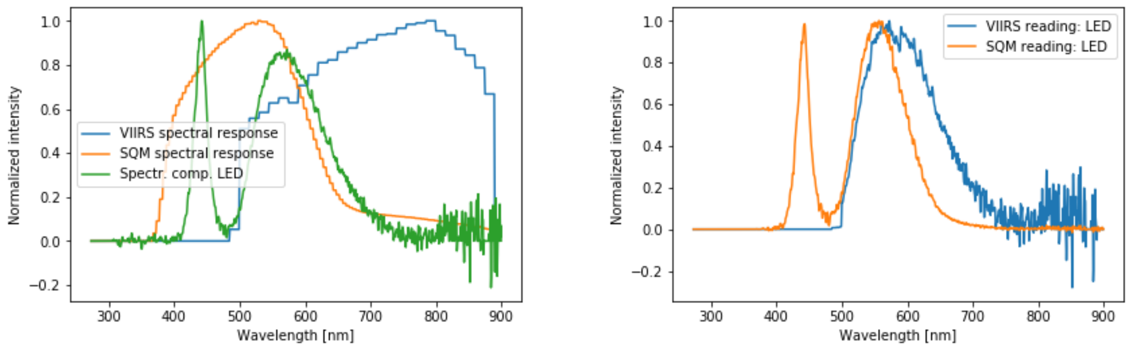


Figure 8: Spectral response curves of VIIRS & SQM and spectral composition of a LED (left) VIIRS & SQM reading of the spectral composition of a LED (right)

The specific artificial sources analysed were Philips RoadStar-GPLS-49 Streetlight (LED), Philips Helios Streetlight (High Pressure Sodium), Sylvania A21 Domestic (Incandescent), Philips - Industrial (Metal Halide) and Globe BR30 Domestic (Halogen) [available on: https://lspdd.org/app/en/lamps]. The spectral response curve for the VIIRS was obtained from [https://ncc.nesdis.noaa.gov/VIIRS/VIIRSSpectralResponseFunctions.php]. The spectral response from an SQM was obtained from [Sánchez de Miguel 2017, et al]. Lastly the spectral composition of the moon was obtained from [http://www.olino.org/blog/us/articles/2015/10/05/spectrum-of-moon-light]. All the intensities worked with in this stage are relative.

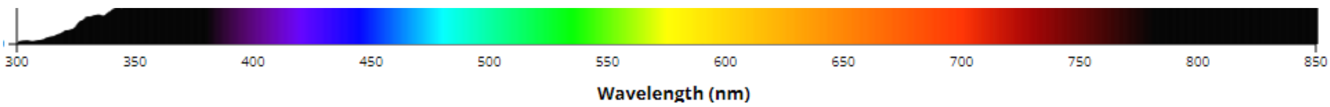


Figure 9: Colour wavelength reference for the spectral compositions

For a brightness reference of the VIIRS and SQM the measurements at Lauwersoog from [Vulto 2021] were used. These amount to VIIRS: $1.95\ nW\ cm^{-2} str^{-1}$ (nano Watt per square centimetre steradian) and SQM: $0.22\ mcd\ m^{-2}$ (microcandela per square metre). To convert between the two different units of the brightness references a unit conversion of $1\ mcd\ m^{-2} = 0.14641288433382\ nW\ cm^{-2}\ str^{-1}$ was used obtained from [https://www.translatorscafe.com/unit-converter/en-US/illumination/7-11/candela%20steradian/meter%C2%B2-watt/centimeter%C2%B2%20(at%20555%20nm)/]. This means the SQM reference can be equated to $1.51\ nW\ cm^{-2}\ str^{-1}$.

With the brightness references, the scaling factor for each spectral composition reading for the VIIRS and the SQM can be computed. The scaling factor represents how much the VIIRS or SQM reading has to be scaled for a sole (artificial) light source to fully contribute to the brightness reference. This way the different types of ALAN sources can be compared to natural moonlight. First the area under each correlated spectral composition was determined by taking the integral of the Figure. Then the scaling factor can be determined via the ratio of this area, which is a brightness computation, and the brightness reference of the VIIRS or SQM.

The next step in this analysis is how the different ALAN sources behave in coastal water as it propagates downward. To be able to assess how much light is propagating through coastal water the scattering of light through water depth was computed assuming Rayleigh scattering. This is to an extent in accordance with the National Ocean and Atmospheric Administration, as blue light gets scattered away more than longer wavelengths. What Rayleigh scattering does not compute is the absorption of the longer wavelengths as is also present in Figure 10.

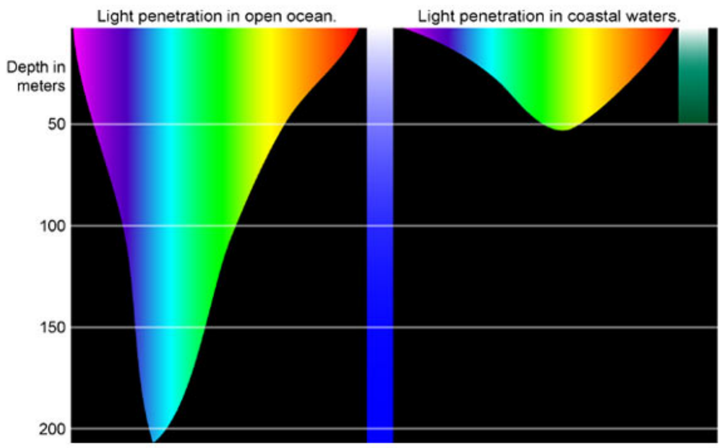


Figure 10: Light penetration in open ocean vs coastal waters [available on: https://oceanexplorer.noaa.gov/explorations/04deepscope/background/deeplight/media/diagram3.html]

Rayleigh scattering can be described as: $I_R = I_1 N l \Omega \epsilon (\frac{d\sigma}{d\Omega})$. The I_R relates to how much light is scattered. N is the number density, l is the path length, Ω is equal to the solid angle scattered and ϵ is the optical transmission efficiency. It can be stated that $\frac{d\sigma}{d\Omega} = \frac{4\pi^2 (n-1)^2}{N_0^2} \frac{1}{\lambda^4}$. So how much light is scattered in coastal water can be related to: $I_R(\lambda) \propto \frac{I_1(\lambda) l}{\lambda^4}$ with l being the water depth in nanometre. How much light is not scattered is then: $I_{TP} = I_1 - \frac{I_1(\lambda) l}{\lambda^4}$. This throughput was then computed for each of the light source spectra at water surface level, 15 metre depth and 30 metre depth. These steps were chosen because from observation of Figure 10 almost all blue light is scattered away around 30 metres of depth.

2.3 Dark sky maps

For the light pollution data maps NASA's Black Marble product [available on:https://worldview.earthdata.nasa.gov/?v=-9.879439530995963,46.649058944166693,22.976751499454355,62.52824434671154&l=VIIRS_SNPP_DayNightBand_At_Sensor_Radiance,Reference_Labels_15m(hidden),Reference_Features_15m(hidden),Coastlines_15m(hidden),VIIRS_Black_Marble,VIIRS_SNPP_CorrectedReflectance_TrueColor(hidden),MODIS_Aqua_CorrectedReflectance_TrueColor(hidden),MODIS_Terra_CorrectedReflectance_TrueColor(hidden)&lg=false&t=2021-01-15-T17%3A18%3A03Z], The World atlas from [Cinzano 2001, et al] and David Lorentz' maps [available on:https://djlorenz.github.io/astronomy/lp2020/overlay/dark.html] were reviewed for the Wadden Sea area. The data is given in irradiance units, in nano watt per square centimetre steradian or magnitude per square arcsecond. This is in contrast to many studies regarding effects of ALAN on marine and avian species, which were either given in lux, or the light source used was of a specific colour and/or intensity. As mentioned before dark sky data measurements (satellite or SQM) cannot distinguish colour so the comparison of the current exposure of ALAN sources in the Wadden Sea and the effect it has on marine and avian species were limited to educated estimates and assumptions.

3. Findings

3.1 Dark sky

The natural light cycle of day and night has been a constant interval of light and darkness for as long as life began to flourish on our planet [Gaston 2013, et al]. The need for humans to light up the night is increasing ever so quickly [Hölker 2010, et al] and the implications of this practice is starting to be researched only recently. Especially for marine environments [Davies 2013, et al]. According to [Davies 2013, et al], in 2010 54.3% of Europe's coastline was already affected by nighttime light pollution. To indicate a threshold, a comparison of common light sources, natural and artificial, is given below.

	Lux
Full sunlight	103000
Partly sunny	50000
Cloudy day	1000–10000
Full moon under clear conditions	0.1–0.3
Quarter moon	0.01–0.03
Clear starry night	0.001
Overcast night sky	0.00003–0.0001
Operating table	18000
Bright office	400–600
Most homes	100–300
Main road street lighting (average street level illuminance)	15
Lighted parking lot	10
Residential side street (average street level illuminance)	5
Urban skyglow	0.15

Figure 11: Variation in illuminance of some common light sources given in lux [Gaston 2013, et al]

As can be seen, skyglow from urban areas can reach illumination levels equal to that of a full moon. Meaning nighttime lighting can produce an eternal full moon scenario for coastal areas with urban settlements closebly, which would be assumed to interfere with monthly and seasonal rhythms of marine species [Gaston 2013, et al]. Direct artificial sources such as lit up offshore oil platforms and windparks, or lights from fishing and research vessels are even brighter when exposed to directly and can be a different form of stressor for marine and avian species [Davies 2013, et al].

3.1.1 Black Marble

As previously mentioned the Wadden Sea is a UNESCO World Heritage site [https://whc.unesco.org/en/list/1314/]. As will become evident shortly, reducing and preserving the Wadden Sea's exposure to light pollution is critical to its longevity. Modelling the actual situation of nighttime lighting relevant for marine and avian species in the Wadden Sea proves to be quite a task. Models that take into account atmospheric reflection and scattering are quite young [Bennie 2014, et al; Cinzano 2001, et al]. This is partly because in 2011 NASA launched the Suomi National Polar Partnership (SNPP) satellite carrying the Visible Infrared Imaging Radiometer Suite (VIIRS) instrument [Elvidge 2022, et al]. This newly obtained VIIRS data is far superior to the previous way to collect global low light imaging data. Which was via the U.S. Air Force Defence Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) [Elvidge 2022, et al]. In 2017 NASA introduced the Black Marble Nighttime At Sensor Radiance (Day/Night Band) product, which makes use of the VIIRS instrument.

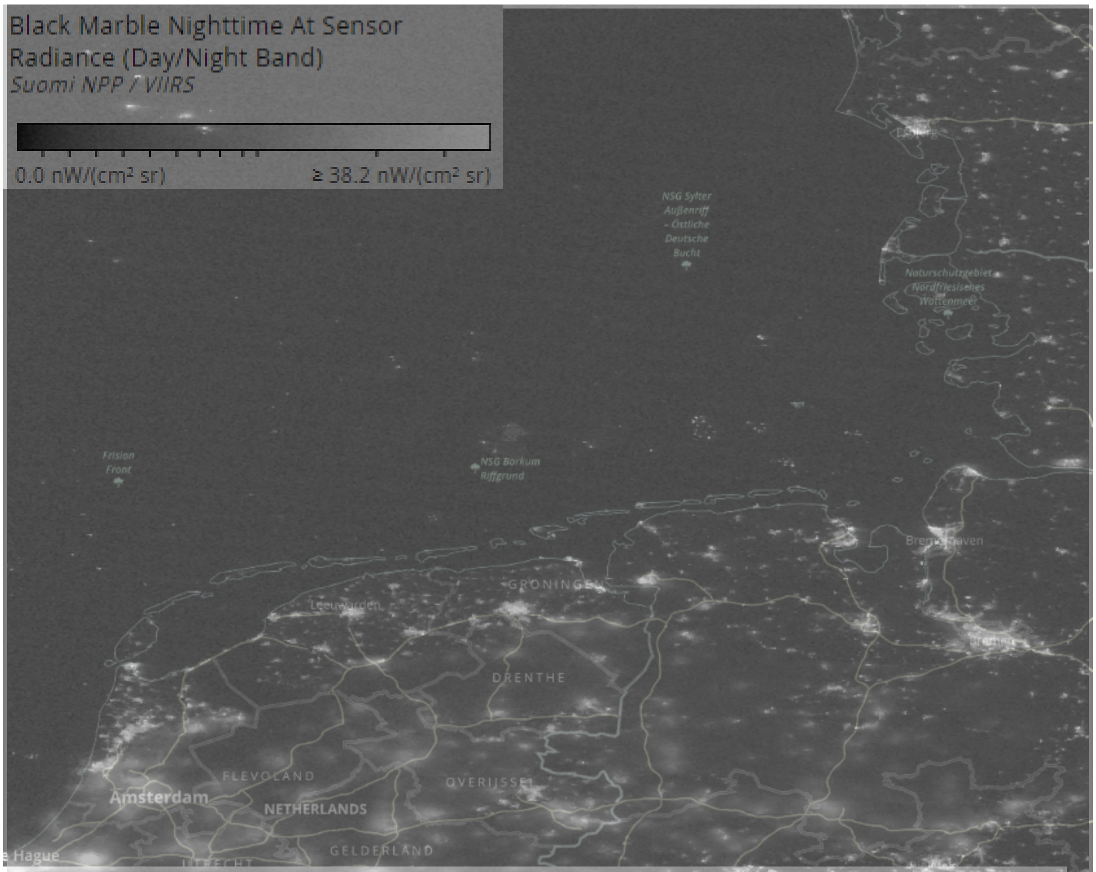


Figure 12: NASA's Black Marble low light imaging product of the Wadden Sea on 26/04/2022 [available on:https://worldview.earthdata.nasa.gov/?v=-9.879439530995963,46.64905894416693,22.976751499454355,62.52824434671154&l=VIIRS_SNPP_DayNightBand_At_Sensor_Radiance,Reference_Labels_15m(hidden),Reference_Features_15m(hidden),Coastlines_15m(hidden),VIIRS_Black_Marble,VIIRS_SNPP_CorrectedReflectance_TrueColor(hidden),MODIS_Aqua_CorrectedReflectance_TrueColor(hidden),MODIS_Terra_CorrectedReflectance_TrueColor(hidden)&lg=false&t=2021-01-15-T17%3A18%3A03Z]

Though the Black Marble project is an important breakthrough in the research towards nighttime lighting and its consequences [worldview.earthdata.nasa.gov], it does not modulate atmospheric conditions well enough. For example it shows the Wadden Sea as near to full black because there are almost no light sources present, however light pollution relevant to ecological consequences does not only come from direct sources but also from horizontally propagated light, which can be subject to reflection and scattering [Cinzano 2001, et al].

3.1.2 VIIRS & SQM assessment

A quantitative analysis of the VIIRS and SQM measurement technique was carried out for 5 different types of ALAN sources. As explained in the methods, first the spectral response of the day-night band of the VIIRS [available at: https://ncc.nesdis.noaa.gov/VIIRS/VIIRSSpectralResponseFunctions.php] and the SQM [Sánchez de Miguel 2017, et al] were correlated to the spectral compositions of the ALAN sources and the spectral composition of the moon [[http://www.olino.org/blog/us/articles/2015/10/05/spectrum-of-moon-light].

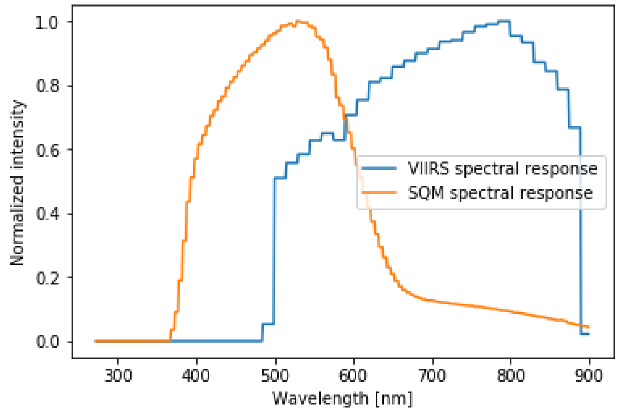
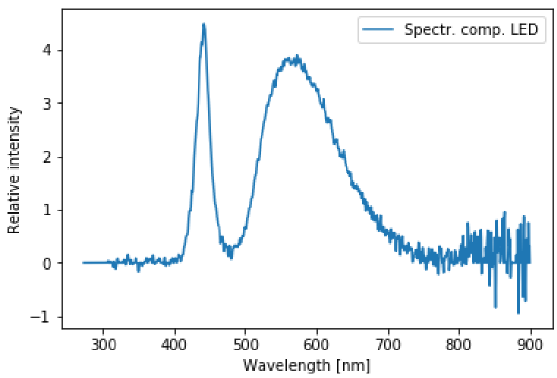


Figure 13: Spectral response of the day-night band of the VIIRS (blue) & the SQM (orange)

An example why this is significant is immediately recognizable for the spectral composition of a LED. The spectral composition and the reading of the LED is shown below. The spectral composition and the reading of all the 5 ALAN sources and the moon are presented in the appendix.



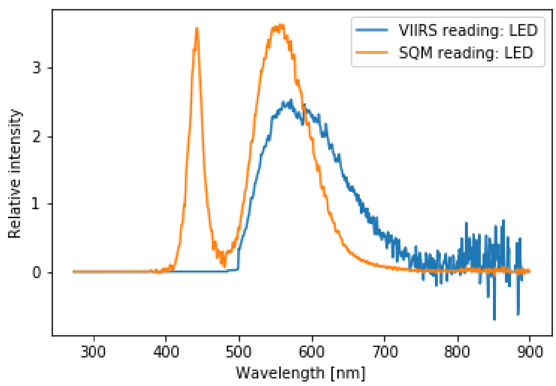


Figure 14: Spectral composition of a LED (left) & the VIIRS day-night band reading and SQM reading of the spectral composition of a LED (right)

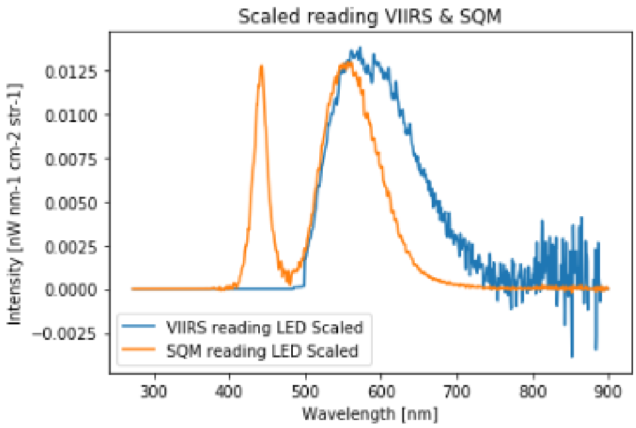
As can be seen in Figure 14 the day-night band of the VIIRS does not observe wavelengths smaller than 500 nm. The SQM does not observe wavelengths in the near infrared range. The tiny amount of response for the near infrared wavelengths is suggested to result from the infrared rejection filter not completely covering the optical path [Sánchez de Miguel 2017, et al]. This shows that a combination of the two measurement techniques would result in a more accurate representation of an artificial sky brightness measurement.

The areas under the right graph of Figure 14 represent a brightness. Taking the ratio of this brightness with a VIIRS or SQM brightness measurement such as the one at Lauwersoog from [Vulto 2021] results in a certain scaling factor. This scaling factor represents how much the spectral composition would have to be scaled for it to fully contribute to the brightness measurement of the VIIRS or the SQM, assuming only that type light source is responsible for the brightness measurement. For each type of ALAN source the scaling factor for the VIIRS reading and the SQM reading was determined. LED (Light Emitting Diode), HPS (High Pressure Sodium, INC (Incandescent), MH (Metal Halide), HALO (Halogen).

Type	**VIIRS scaling factor**	**SQM scaling factor**	**Difference**
Moon	0.00474	0.00552	-0.00078
LED	0.00547	0.00358	0.00190
HPS	0.00439	0.00454	-0.00015
INC	0.00398	0.00928	-0.00530
MH	0.00567	0.00366	0.00202
HALO	0.00400	0.00887	-0.00486

Table 1: Scaling factor of the VIIRS & SQM brightness reference at Lauwersoog [Vulto 2021] for different types of light sources

Ideally the VIIRS scaling factor and the SQM scaling factor are the same. However as can be seen in table 1, they are not. The reason for this can be the contribution of a certain region's brightness being made up of multiple different types of artificial light sources.
To check whether the scaling factor was computed correctly, the scaling factor can be multiplied with the VIIRS & SQM readings of the spectral compositions of the ALAN sources. The area under the scaled down graphs should then be equal to the brightness measurements at Lauwersoog from [Vulto 2021] for the VIIRS & SQM respectively.
VIIRS measurement at Lauwersoog: $1.95\ nW\ cm^{-2} str^{-1}$ [Vulto 2021]
SQM measurement at Lauwersoog: $1.51\ nW\ cm^{-2}\ str^{-1}$ [Vulto 2021]

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Area under VIIRS reading: 1.947450980392157 nW cm-2 str-1
Area under SQM reading: 1.513019269588892 nW cm-2 str-1
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Figure 15: VIIRS & SQM reading of a LED scaled down by its corresponding scaling factor

With the scaling factors computed the behaviour of the ALAN sources in coastal water was assessed. The amount of light that not gets scattered (I_{TP}) was determined to be proportional to: $I_{TP}(\lambda) \propto I_1 - \frac{I_1(\lambda)l}{\lambda^4}$. The throughput for each of the light sources (original spectral compositions) scaled down with the corresponding scaling factors at different depths are presented below:

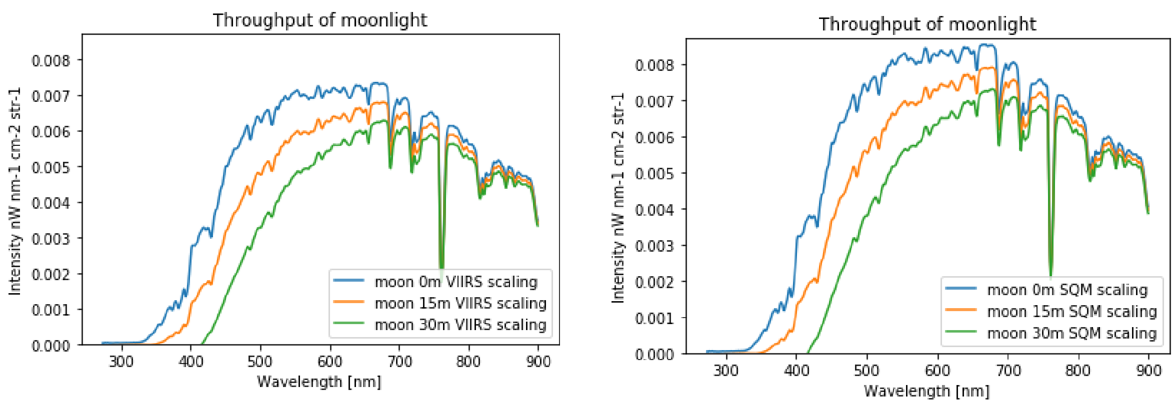

Figure 16: Throughput of spectral composition of moonlight in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

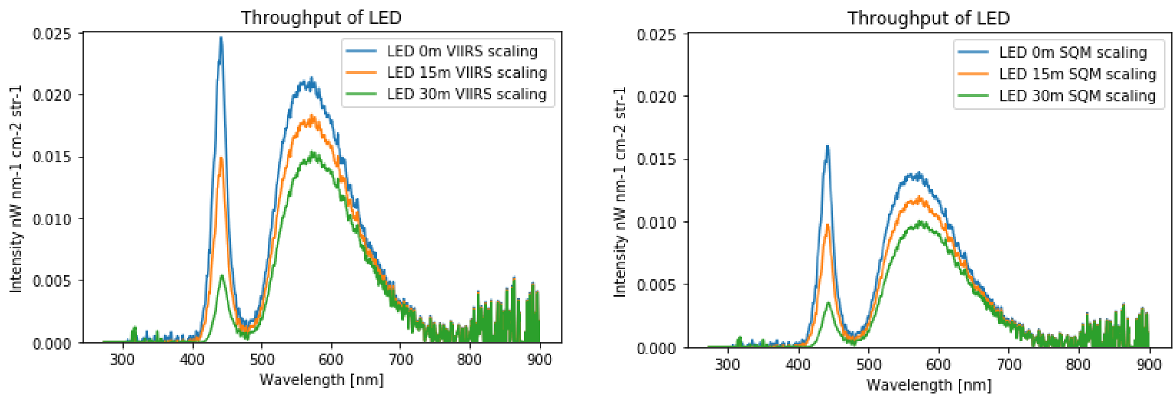

Figure 17: Throughput of spectral composition of LED light in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

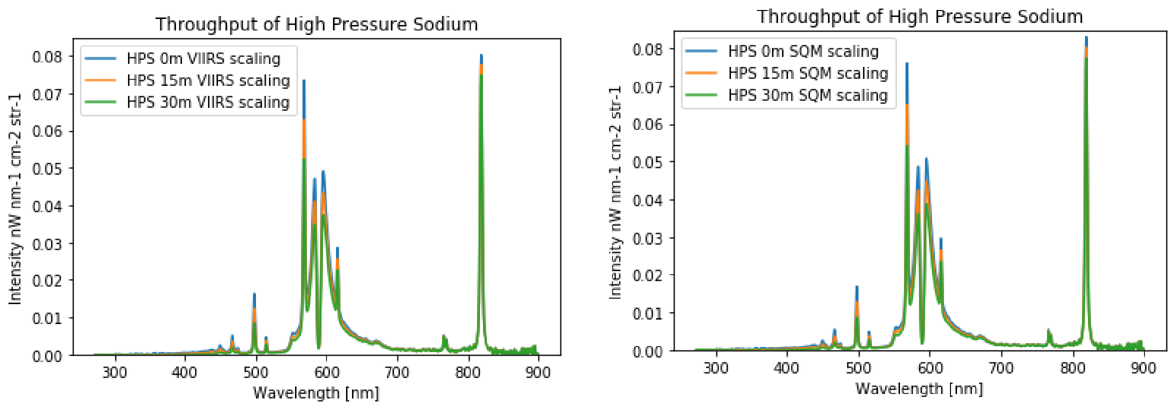

Figure 18: Throughput of spectral composition of High Pressure Sodium light in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

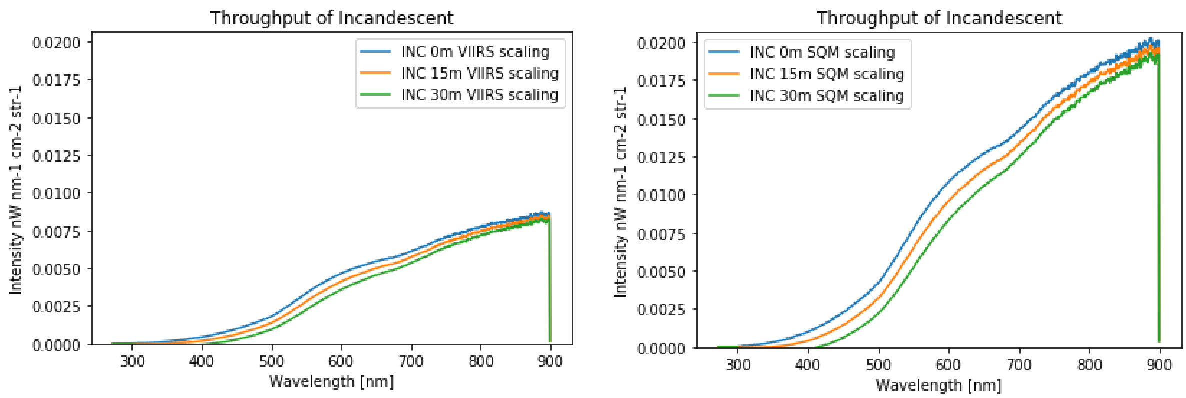

Figure 19: Throughput of spectral composition of Incandescent light in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

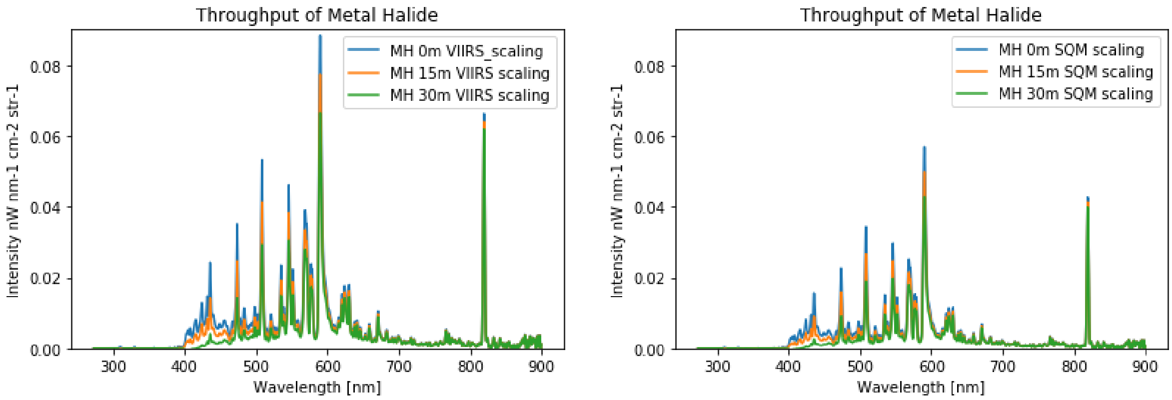

Figure 20: Throughput of spectral composition of Metal Halide light in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

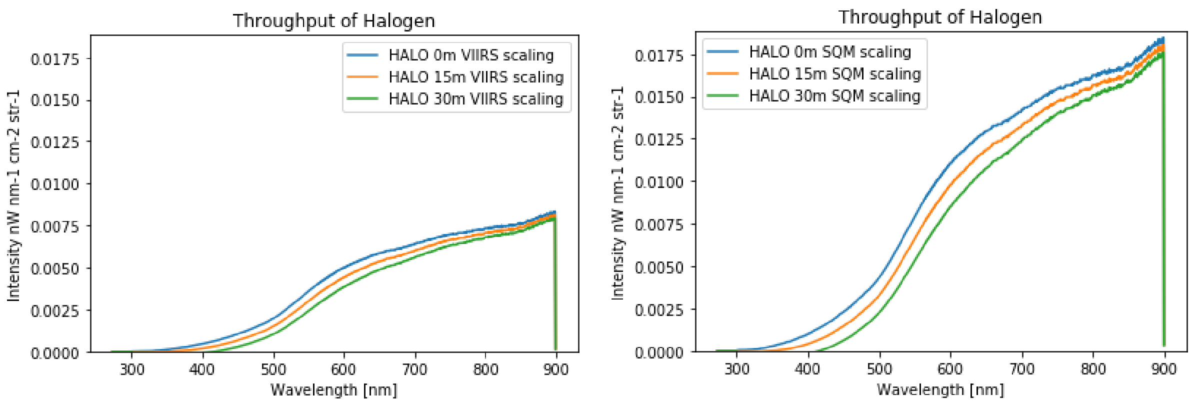

Figure 21: *Throughput of spectral composition of Halogen light in coastal water at different depths scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)*

As can be seen in the Figures, shorter wavelengths get scattered more than longer wavelengths. This is most evident in Figure 17. Figures 17 to 21 will be used for the analysis of the ecological impacts of ALAN sources on marine species in comparison to moonlight. Note that the intensities for the red are not well represented as red wavelengths get absorbed as it propagates through water.

3.1.3 Mapping artificial night sky brightness

Perhaps a frontrunner in modelling the atmospheric light pollution is [Cinzano 2000, et al]. His designed model is still based on data from the DMSP OLS, but does take into account extinction along light paths, double scattering of light from atmospheric molecules and aerosols, Earth's curvature and aerosol content of the atmosphere [Cinzano 2000, et al]. In 2001 [Cinzano 2001, et al] released the first world atlas of the artificial night sky brightness, based on data from the DMSP OLS and his own developed model. The maps show the artificial sky brightness in the Visual band. The latest world atlas P. Cinzano released was in 2015 together with [Falchi 2016, et al] and is based on the combination of VIIRS data and SQM measurements from both professionals and citizen scientists [Falchi 2016, et al]. David Lorenz has recalculated P. Cinzano's atlas using the most recent VIIRS data and produced more recent maps showing light pollution based on Cinzano's model. These maps are again in the V-band and given in units of magnitude per square arcsecond [available on:https://djlorenz.github.io/astronomy/lp2020/overlay/dark.html]. Unfortunately it is not possible to convert this measurement to lux so D. Lorentz implemented a more intuitive reading as well on the bottom. Namely the fraction of artificial sky brightness to natural sky brightness, i.e. 2 means the artificial sky brightness is twice as bright as the natural sky brightness. The calculated maps of D. Lorentz can be seen in the figures below.

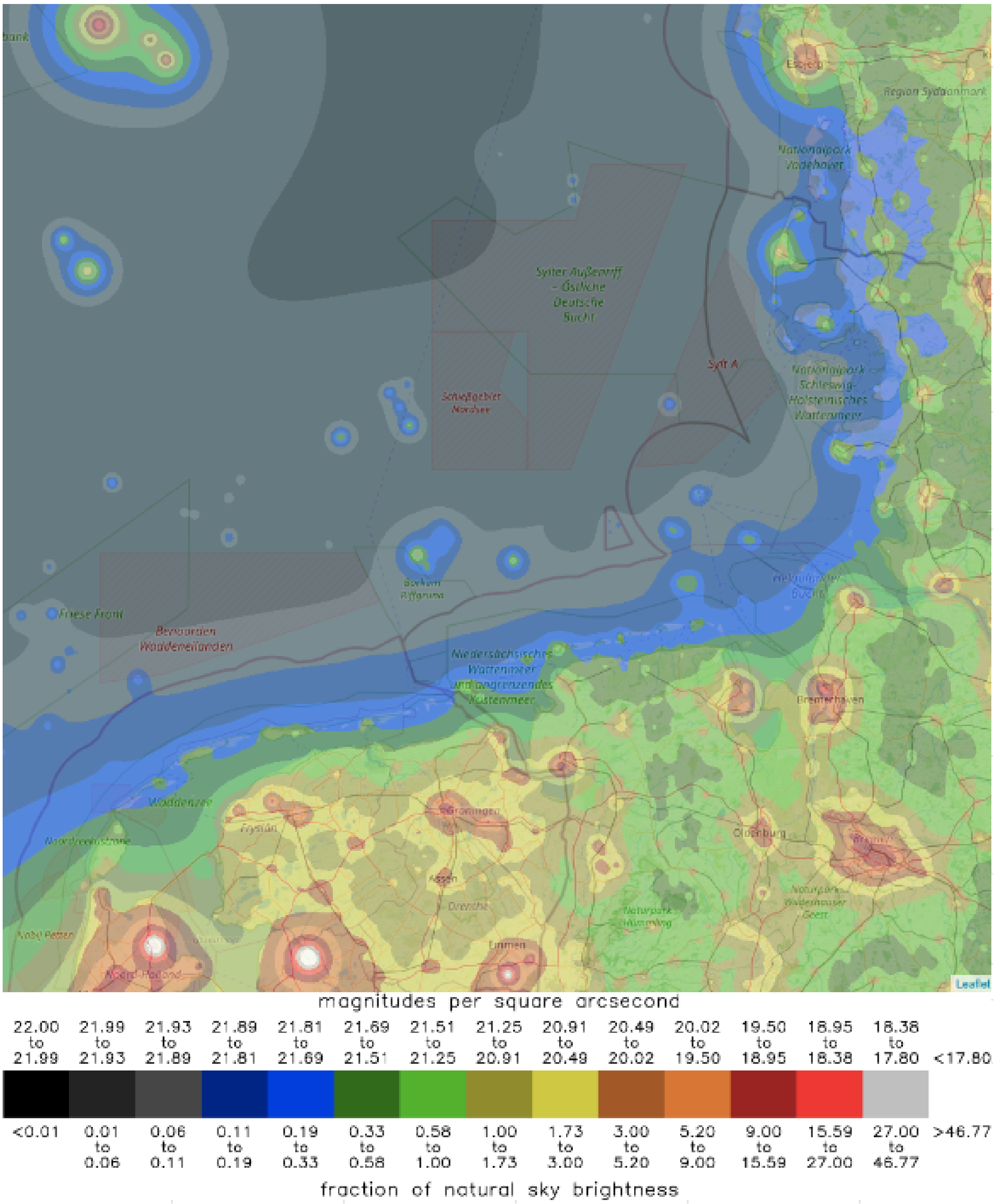

Figure 22: Current state (2020) of artificial sky brightness modelled in the Wadden Sea. [available on: https://djlorenz.github.io/astronomy/lp2020/overlay/dark.html]

D. Lorentz also developed a trend map, comparing the artificial sky brightness maps he computed throughout the years of 2014 to 2020 [available on:https://djlorenz.github.io/astronomy/lp2020/overlay/dark.html]. This map clearly shows that artificial sky brightness has increased in numerous areas in the Wadden Sea.

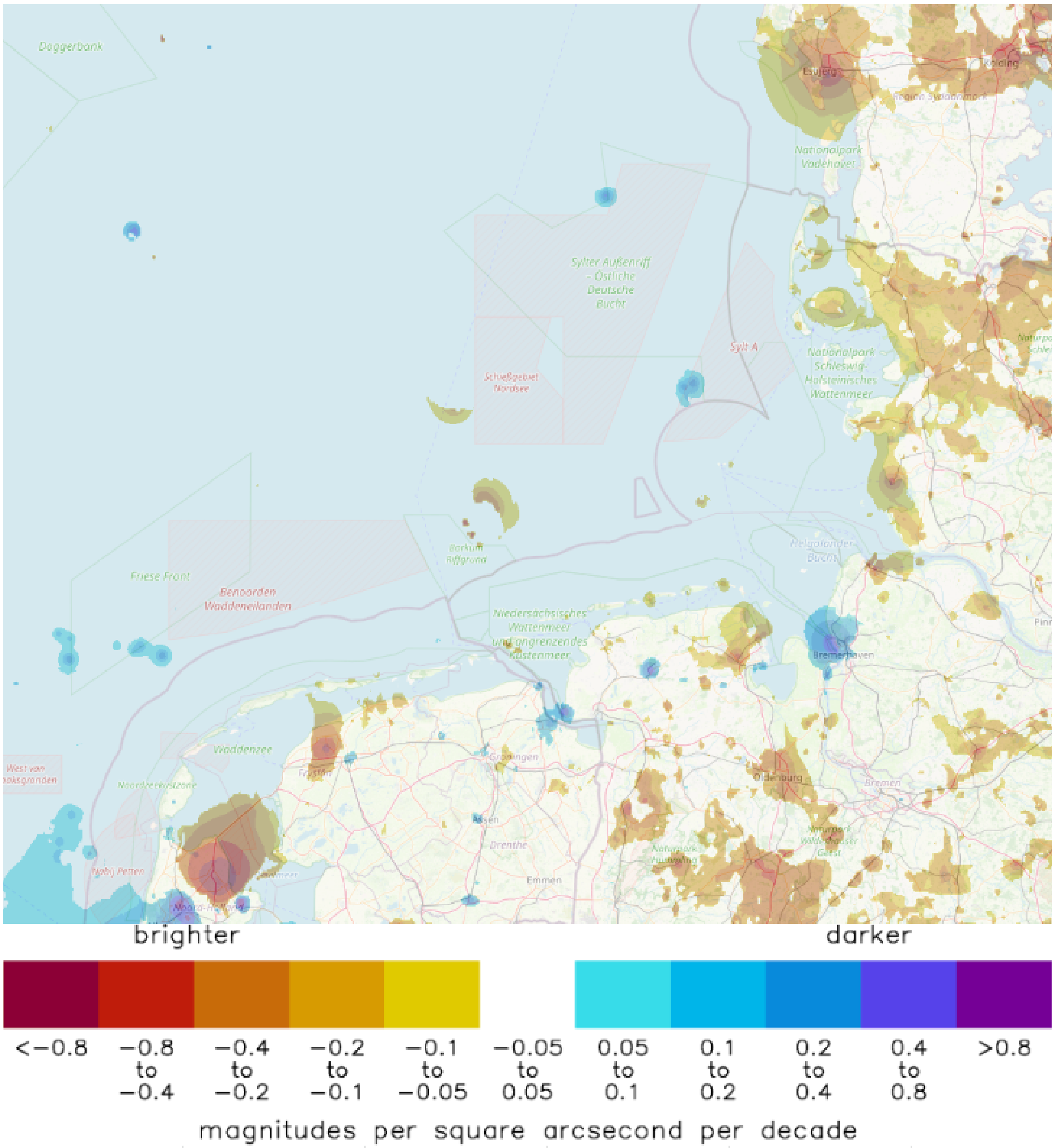

Figure 23: Light pollution satellite data trend of the Wadden Sea between 2014-2020 [available on:https://djlorenz.github.io/astronomy/lp2020/overlay/dark.html]

What the ecological implications are regarding the exposure to light pollution for the Wadden Sea is still to be precisely researched. Though numerous studies on how avian and recently marine species react to ALAN have been carried out, the scale of the consequences for the Wadden Sea are unknown.

3.2 Birds

The impact of light pollution on birds is relatively well researched [Adams 2021, et al]. Concerns about birds colliding with lighthouses and other lit structures has been documented as early as the late 1800's [Rich 2006, et al]. Many migratory waterbird species migrate at night and are known to be attracted to artificial light at night [Chernetsov 2016, et al; Krop-Benesch 2022, et al; Rich 2006, et al; Zapata 2018, et al]. For the Wadden Sea this would of course pose a problem since it is one of the most important areas for many species of migratory birds. The Wadden Sea is essential for 41 migratory waterbird species that make use of the East Atlantic Flyway and it has been estimated that each year up to 12 million birds use the area for either breeding, moulting or wintering [waddensea-worldheritage.org]. While death or injury on collision with lit up structures [Health Council of the Netherlands 2000; Hüppop 2006, et al; Rich 2006, et al] is the most adverse effect illumination has on the Wadden Seas migratory bird population, other implications such as light trapping [Rich 2006, et al] or physiological changes [Mulheim 2016, et al] attributed to ALAN have also been studied.

*Figure 24: Illustration of the Eddystone lighthouse, Plymouth England, by M.E. Clarke, with migratory birds circling around the lantern [*Clarke 1912, et al*]*

3.2.1 Migratory birds orientation

The mechanisms of bird orientation are not fully understood, but it is believed birds use a combination of landmarks, celestial light cues and perception of the Earth's magnetic field [Krop-Benesch 2022, et al; Mulheim 2016, et al]. It is unknown whether there exists a hierarchy between these mechanisms, but magnetoreception is believed to be the principal mode of orientation [Gaston 2013, et al]. It is to be expected that for celestial light cues ALAN can and will be disruptive. Migratory birds are for example known to be influenced by the lunar cycle since birds experience significantly less attraction to ALAN on bright, clear nights with a full moon [Verheijen 1980, et al]. Also during poor weather conditions such as foggy low cloud cover, birds tend to aggregate more towards the bright concentrated beams of light originating from artificial sources [Rich 2006, et al].

Exactly why birds are attracted to light and try to avoid darkness is still being researched, but it could be related to a bird's magnetic compass, since the magnetic compass does not function in complete darkness [Krop-Benesch 2022, et al; Mulheim 2016, et al].

Recent studies towards bird magnetic field orientation mechanisms have shown that birds actually have a light-dependent magnetic compass [Mulheim 2016, et al]. It is believed that light induces biochemical reactions in specialised receptor molecules which makes birds perceive the Earth's magnetic field [Mulheim 2016, et al]. It's been studied that the effectiveness of this orientation is dependent on the direction and polarisation of the light [Mulheim 2016, et al] and [Mulheim 2016, et al] suggests that the visual system is, to a certain degree, involved in the magnetoreception process. Research suggests that birds' visual cues work best under 'white' light and that monochromatic light, meaning a light source emitting a specific wavelength, disrupts their ability to orientate themselves via visual cues as well as their magnetic compass [Mulheim 2016, et al]. Altering the polarisation of the light via ALAN is also expected to disrupt the magnetoreception of birds. It's been shown that birds react differently to different wavelengths [Mulheim 2016, et al], however if the light is strong enough birds can orient in the wrong direction regardless [Chernetsov 2016, et al].

Consequences for these disruptions can be seen in a North American study where it is suggested migratory birds altered their natural migratory route because of the attraction to areas with high levels of ALAN [La Sorte 2022, et al]. Such a deviation to the natural order of things can cause delayed arrival to breeding or wintering grounds for the Wadden Sea. ALAN can also be the cause of reducing energy stores necessary for birds to get to their destination, since it has been observed that the birds are reluctant to leave the lit up area [Rich 2006, et al; Verheijen 1980, et al]. This 'light trapping' has been recorded as a prominent mortality cause for migrating birds, where the birds circle lit up oil platforms for hours or days on end till eventually falling down to the ocean or, less often, on the platform [Rich 2006, et al]. The reduction of energy reserves and delayed arrival to the breeding and wintering grounds associated with the attraction to ALAN can have serious consequences for survival and subsequently reproduction of migratory bird species [Rich 2006, et al].

3.2.2 Change of activity time & physiology

The impact ALAN has on birds is not constrained to migration alone. Coastal breeding birds or shorebirds also suffer from increasing levels of ALAN. Ecological light pollution is not only affecting the birds as an altered view of the environment, but the artificial light can affect the birds on a physiological level as well. For example it has been shown that light levels of already 0.3 lux are sufficient to suppress melatonin production in black birds [Grubisic 2019, et al]. Melatonin is a hormone that controls the biological clock of species and essentially tells them when to go to sleep, or for nocturnal species when to become active [Tordjman 2017, et al]. For young and adult Great Tits it has been determined that exposure to ALAN dramatically affects sleep behaviour because of a greater activity time, and consequently causes an increase in levels of stress hormones and reduced ability of the immune system [Raap 2016, Casasole et al; Raap 2016, Pinxten et al].

Songbirds have also been shown to have a greater activity time. Research has shown that ALAN alters the seasonal rhythm of dawn and dusk singing in common European songbirds [Da Silva 2015, et al]. More explicitly multiple species were observed to start earlier at dawn and extend their evening song, only due to artificial night lighting.

Shorebirds searching for food (foraging) do so during the low tide at day or night time, preferring the day time. Shorebirds scout for food either visually or tactically. Visual feeders especially prefer daytime low tide foraging, while tactile feeders can also forage at low light levels and are able to switch between a visual or tactile strategy [Zapata 2018, et al]. ALAN illumination, at first glance, can be seen as beneficial for these shorebirds. Areas that are constantly illuminated by artificial light provide an excellent foraging ground. It has been shown that for an estuary in Northern Europe, shorebirds preferred sight-based foraging over tactile foraging in highly illuminated areas independent of lunar phase and cloud cover [Dwyer 2012, et al]. Such, it can be concluded that ALAN affects the foraging behaviour of these shorebirds and though it may be beneficial for the individual bird, locally the availability of biomass for foragers can be reduced [Krop-Benesch 2022, et al].

Furthermore it has also been shown that ALAN affects the reproduction process of birds. Research suggests that female blackbirds perceive even low levels of ALAN as a chronic stressor, which leads to a reduced secretion of reproductive hormones [Russ 2015, et al]. For some bird species ALAN has been identified as the cause for either an advancement [Dominoni 2013, et al] or delay [Senzaki 2020, et al] of the start of the breeding process.

3.2.3 Analysis

Whether the known ecological effects of light at night on birds actually affect the Wadden Sea is difficult to quantify. In the most recent report of migratory and wintering waterbirds in the Wadden Sea it has actually been observed that between 2010/2011-2019/2020 (roughly the same period as the light pollution trend map in Figure 23) most migratory species have increased in population size.

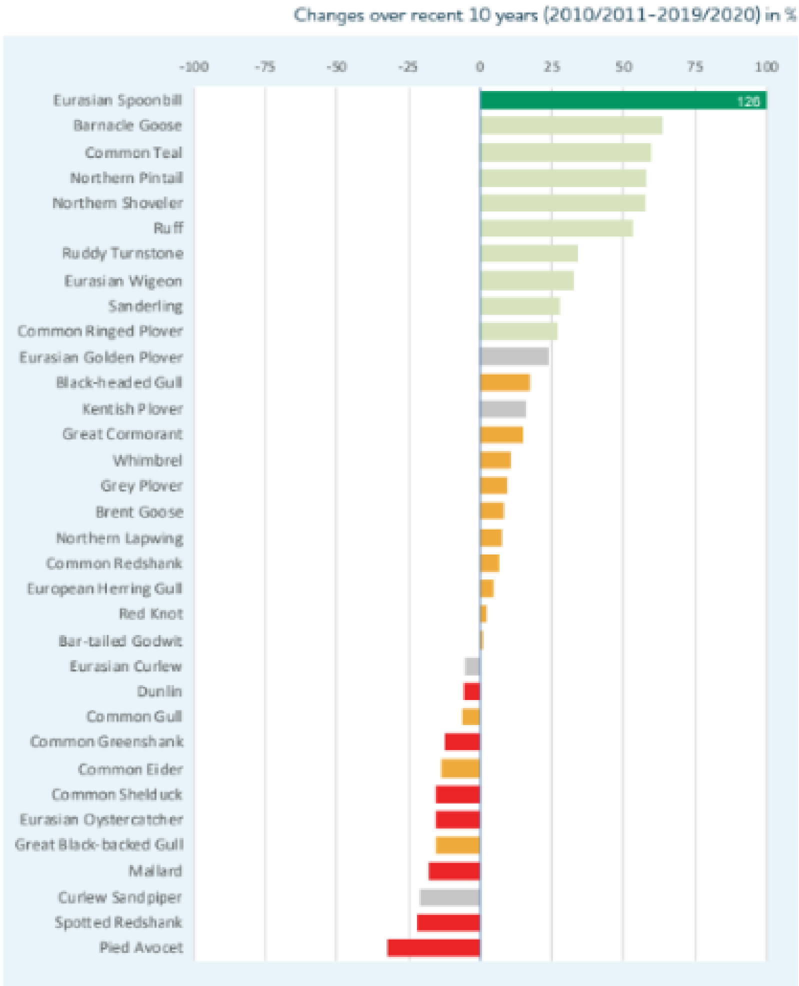

Figure 25: Trend of migratory bird species population in the Wadden Sea between 2010/2011 - 2019/2020 [Kleefstra 2022, et al]

From observation of figure 25 one can determine that the overall migratory bird species population in the Wadden Sea has increased by 114% [Appendix] between 2011-2020. The population size of a migratory bird species however, is affected by a lot of different factors [Kleefstra 2022, et al]. Direct and indirect. Many potentially more prominent than ALAN. Because of this it is near impossible to conclude whether the artificial sky brightness (Figure 22 & 23) and the known ecological effects of ALAN are currently having an effect on the population sizes of the migratory bird species in the Wadden Sea. One would have to almost individually determine whether a bird mortality/breeding success is the result of ALAN and subsequently determine what percentage of all bird mortality cases were caused by ALAN, per species. A humongous task to be sure but the first steps have already been taken. Just recently on may 26 2022, a migration world atlas was released [available on https://migrationatlas.org/]. Tracking individual species around the globe.

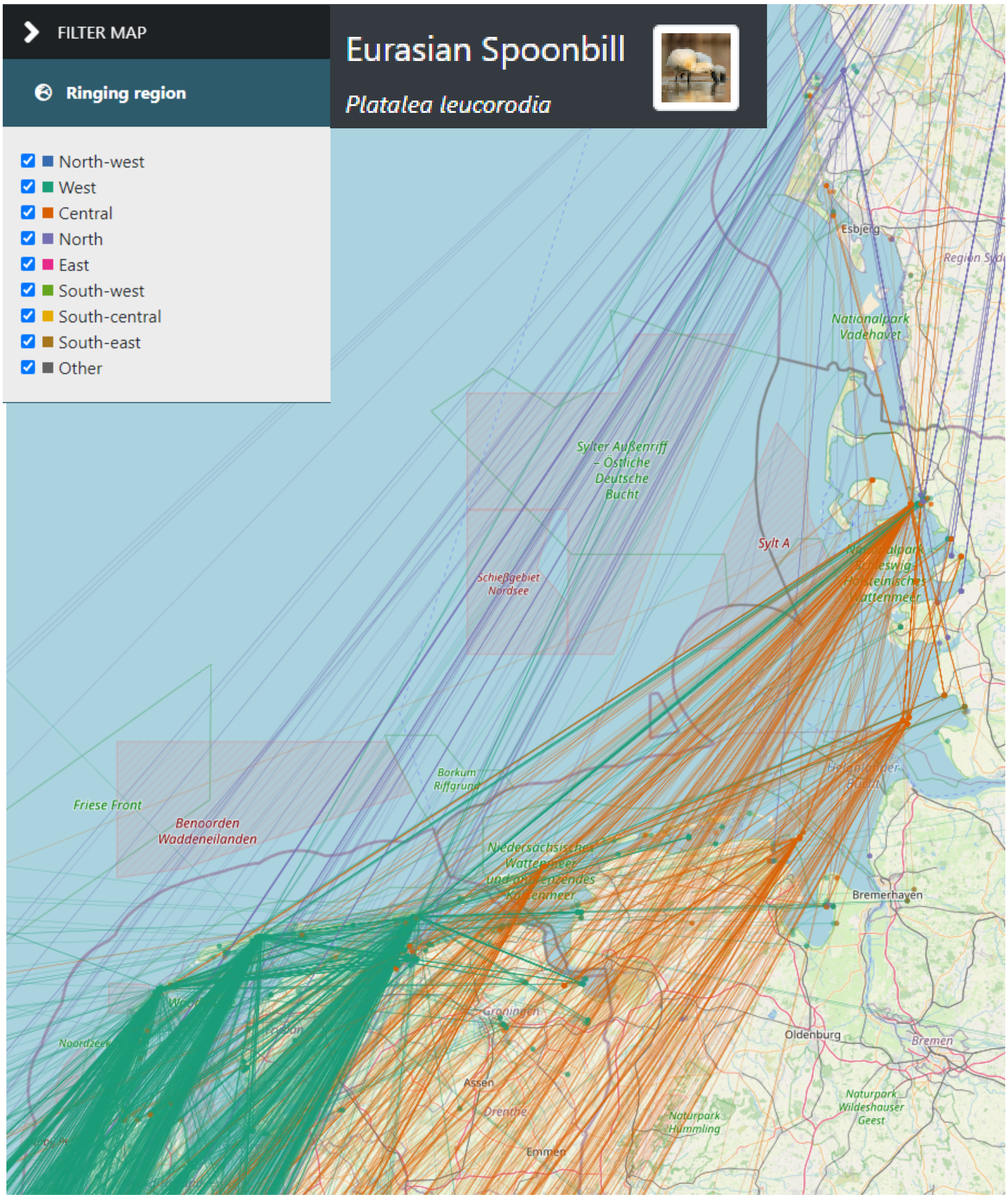

Figure 26: Tracking of the Eurasian Spoonbill in the Wadden Sea region [available on: https://migrationatlas.org/]

This atlas provides tracking information of over 100 individual species. The atlas tracks so-called ring recoveries obtained from electronic devices, principally satellite transmitters, GPS-GSM tags or geolocators. The project already has a condition filter, able to identify the condition of the birds traced. E.g. if the bird is dead/alive, shot on purpose or died from disease or another cause. Together with this dynamic database and further research, an estimate of ALAN effects could be developed for the Wadden Sea region.

For the individual bird it can be determined that the current ALAN levels are highly likely to have a negative effect. As can be seen in Figure 22, closer to the coast artificial sky brightness is estimated to sometimes be equal to that of natural sky brightness. Light levels such as these can be expected to attract/disorientate the bird [Rich 2006, et al] and/or suppress melatonin production [Grubisic 2019, et al].

In summary, ALAN has been shown to attract and affect migrating birds and shorebirds in various ways. It can be expected that these known effects of artificial light on avian species can affect the Wadden Sea's bird populations, through direct mortality or indirect consequences. The extent of these effects on the Wadden Sea is unknown and difficult to study. Nevertheless it can be assumed that ALAN is a considerable ecological stressor for the Wadden Sea and should be keenly monitored in order to better preserve the Wadden Sea's important feeding, breeding and wintering grounds for global bird populations.

Birds	Effect	Consequence	Source
Light as a resource	Magnetic compass disruption	Orientation and migration route disruption	Mulheim 2016, et al; Wiltschko 2009, et al
	Melatonin suppression	Increased activity time, increased stress hormones, reduced immune defence	Raap 2016, Casasole et al; Raap 2016, Pinxten et al
	Reduced reproductive hormones	Impact on breeding succes and population	Russ 2015, et al
	Advanced or delayed breeding process	Disruption of seasonal rhythms	Dominoni 2013, et al; Senzaki 2020, et al
Light as an information source	Attraction to ALAN	Death or injury on collision Light trapping Reduction of energy stores neccesary for migration	Health Council of the Netherlands 2000; Krop-Benesch 2022, et al; Rich 2006, et al; Verheijen 1980, et al
	Disorientation	Delayed arrival at breeding or wintering grounds	Krop-Benesch 2022, et al; Rich 2006, et al; Verheijen 1980, et al
	Shorebirds change of activity times	locally reduced availabillity of biomass	Dwyer 2012, et al; Krop-Benesch 2022, et al

Figure 27: Summary of known and studied ecological effects on light pollution on birds

3.3 Blue mussel and pacific oyster beds

Blue mussels and pacific oysters have for at least two decades been co-existing in the Wadden Sea as dense reef-like structures [Wehrmann 2000, et al]. The pacific oyster however, is a successful invasive alien species mediated by human activities and its development in the Wadden Sea is closely monitored and studied [Nehls 2007, et al; Troost 2010, et al]. Pacific oyster reefs and blue mussel beds in particular are crucial for the availability of biomass in the Wadden Sea for a large number of species, among many of which are birds, and thus serve an important role in the Wadden Sea's food web [Markert 2013, et al; Troost 2010, et al]. The distribution and dynamics of these intertidal beds rely on larval supply, settlement and post-settlement processes [Markert 2009, et al; Troost 2010, et al].

*Figure 28: Left: blue mussels; right: pacific oysters with blue mussels in the interspaces [*available on: https://www.waddensea-worldheritage.org*]*

3.3.1 Larvae settlement

The assemblages of blue mussel beds and pacific oysters are structured vertically, with light intensity and spectral composition playing an important role for site settlement selection [Davies 2013, et al]. The larvae use the intensity and spectral composition of light to identify an optimal settlement zone at a specific depth, because of the different absorption levels of light in water [Mundy 1998, et al]. Artificial light sources emit different spectra than natural light at night. Therefore ALAN can influence the site selection of larvae, resulting in a suboptical settlement selection, which in turn can negatively affect the survival and reproduction of the beds [Davies 2013, et al]. For example it has been shown that larvae of the pacific oyster develop a light sensitive eyespot during the settlement stage that can be influenced by artificial light [Kim 2021, et al]. Pacific oyster larvae were subjected to light-emitting diodes (LEDs) of different wavelengths and intensities. Near ultraviolet, white and green light of specific intensities were observed to disrupt larval settlement, while red and near infrared at specific intensities were observed to induce settlement activities [Kim 2021, et al]. This result raises a concern for the ecological impact of oyster beds and possibly mussel beds, due to the growing interest of LED use in many coastal lighting applications [Davies 2020, et al; Kim 2021, et al; Salvador 2018, et al].

3.3.2 Preference of darkness

The effect of light on mussels and oysters is relevant to not only the larvae stage. A study back in 1985 [Strömgren 1976, et al] already showed that light has an inhibitory effect on post-larvae growth rate for the blue mussel. It was found that a reduced irradiance less than 4 Wm^{-2}caused a significant increase in growth rate. The growth in darkness was 20% greater than in natural light [Strömgren 1976, et al]. A study on blue mussel shell pigmentation found an agreement with this conclusion, determining a 20.5% greater growth in semi-darkness in the early post-larvae stage, in contrast to continuous fluorescent light exposure [Trevelyan 1987, et al].

A study on the blue mussel feeding regime showed that its circadian rhythm (day-night cycle) is heavily influenced by light. Blue mussels exposed to natural light conditions showed higher feeding activity at night, even when they were continuously fed during the day [Robson 2010, et al]. ALAN of course disrupts natural light conditions and may subsequently disrupt the circadian rhythm of blue mussels [Robson 2010, et al].

A study on adult pacific oysters suggests that adult oysters are also light sensitive [Wu 2015, et al]. Pacific oysters were exposed to an LED flashlight while filtering seawater through their shellopenings. It was determined that the degree of opening gradually increased during the exposure period, but rapidly decreased when the LED was turned off [Wu 2015, et al]. The direct and indirect impact of this effect is only speculative, but when the pacific oysters open their shell they are more vulnerable to predators [Wu 2015, et al]. Leading to assume that the light sensitive ability is a predation-avoidance mechanism. ALAN may therefore negatively affect the safety of pacific oysters. Which in turn could result in a negative effect on the pacific oyster population and a locally reduced availability of biomass in the surroundings of artificial light sources. Animals that feed on this biomass, such as many species of birds, can then be negatively influenced as a consequence [Waser 2016, et al]

3.3.3 Analysis

For the Wadden Sea case, there are little to no resources from which can be concluded that the Blue Mussel and/or Pacific Oyster beds are affected by ALAN directly. Survival success of mussel beds in the Wadden Sea are found to be correlated to the bed size, subtidal or intertidal habitat and salinity of the water [Troost 2022, et al]. The population of the blue mussel in the Wadden Sea is declining, but this is largely attributed to the invasion of the pacific oyster [Nehls 2007, et al]. So it is currently not possible to show whether ALAN affects the survival success of the beds as well. There are also little to no studies relating to blue mussel sizes in the Wadden Sea and the one that does show results of size measurements, shows no evidence that ALAN is the cause for smaller sizes as other, perhaps more prominent, factors are suggested [Ricklefs 2020, et al]. Since the blue mussel and pacific oyster beds are either fully or periodically underwater, depending on the habitat, Figures 22 & 23 cannot aid in determining whether ALAN is currently affecting the reefs in the Wadden Sea. Because these artificial sky brightness maps show ALAN in the atmosphere, so for subwatersurface species one would need a model of how light propagates through ocean (salt) water. [Prabhakaran 2018, et al] have made an effort to develop such a model.

In the assessment where it was assumed that light scattered in coastal water according to Rayleigh scattering it can be seen that, when compared to moonlight, LED's can be more disruptive for the blue mussel and pacific oyster larvae, even still at 30m depth.

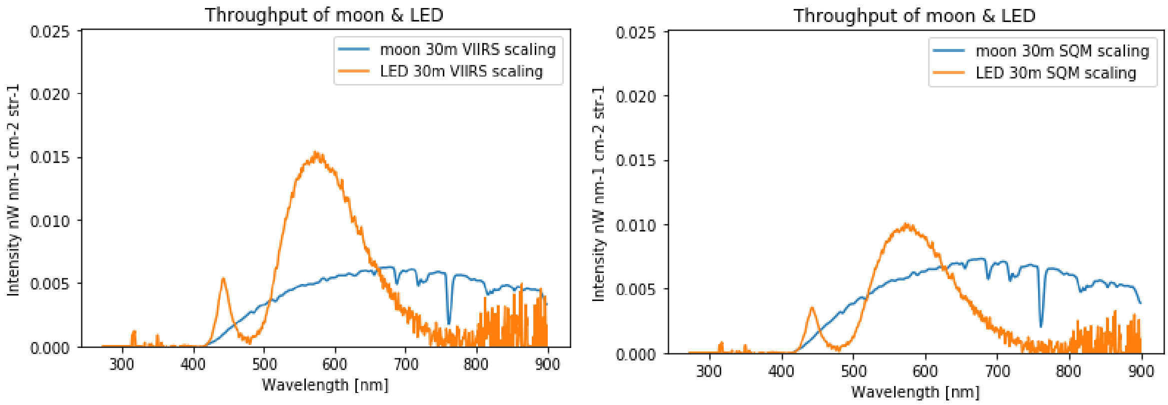

Figure 29: Throughput of spectral composition of LED compared to moonlight at 30 metre water depth scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

Assuming for both the VIIRS brightness reference and the SQM brightness reference at Lauwersoog [Vulto 2021] that the brightness either only comes from the moon or only from a LED source. It can be determined that, even though blue light gets scattered away the most compared to longer wavelengths, the intensity of the blue and green peak at 30m depth of a LED is higher than the blue and green range of moonlight and could potentially be disruptive for larvae settlement selection. This claim is even more supported by Figure 30, showing that the blue part of the LED is of roughly the same intensity at 30 metre, as the blue part of the moon at 1 metre of water depth. Important of note is that the VIIRS does not observe this disruptive blue range of a LED, as can be seen in Figure 15.

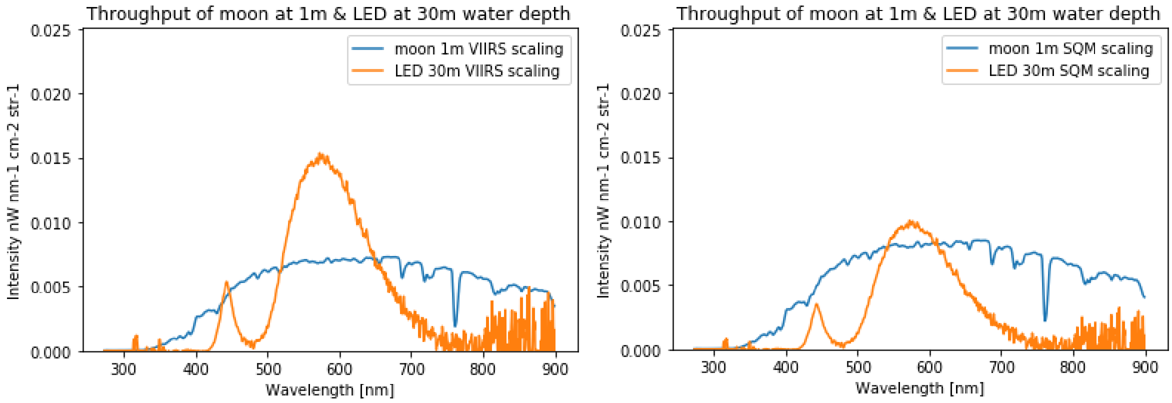

Figure 30: Throughput of spectral composition of moon at 1 metre compared to LED at 30 metre water depth scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

The brightness reference for Lauwersoog [Vulto 2021] is most probably, however, not bright enough for disruption of settlement to occur [Kim 2021, et al]. However this does show that the blue and green wavelengths of LED light sources are expected to result in suboptimal settlement selection for the larvae of the blue mussel and pacific oyster at local spots if the LED sources are bright enough.

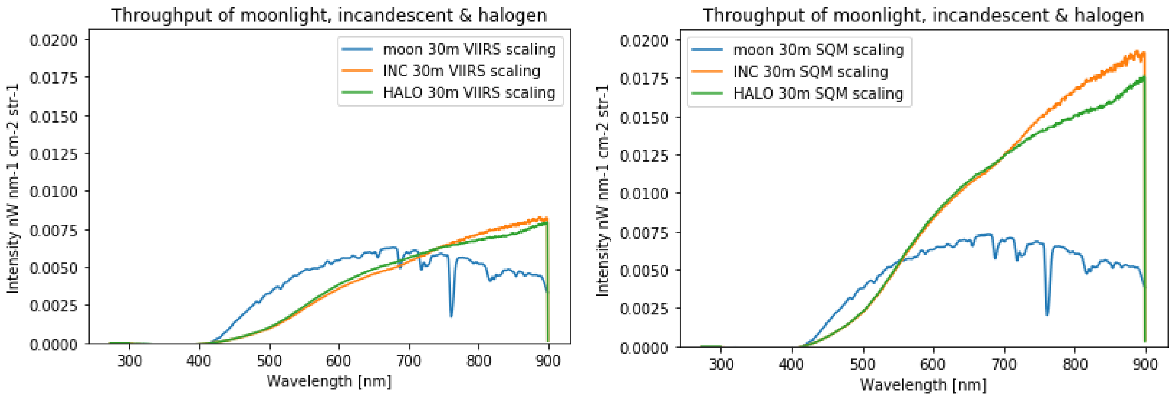

Figure 31: Throughput of spectral compositions of incandescent and halogen compared to moonlight scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

In contrast, if the entire brightness would come from an incandescent or a halogen light source compared to moonlight it could result in less disruptive effects at 30m depth than for a LED. This is because incandescent and halogen light sources do not have high intensity peaks in the blue or green wavelength. It can actually be seen that for the blue wavelength ranges at 30m water depth the intensity for halogen and incandescent is less than that of moonlight. However in the incandescent and halogen case, there is a vast difference between the VIIRS brightness reference and the SQM brightness reference. Thus making it difficult to determine whether the use of an incandescent or halogen light source is more or less disruptive for the blue mussel and pacific oyster than natural moonlight. Nevertheless it can be assumed for both the incandescent and the halogen light source, since they emit a warmer colour, they do not disrupt larvae settlement selection.

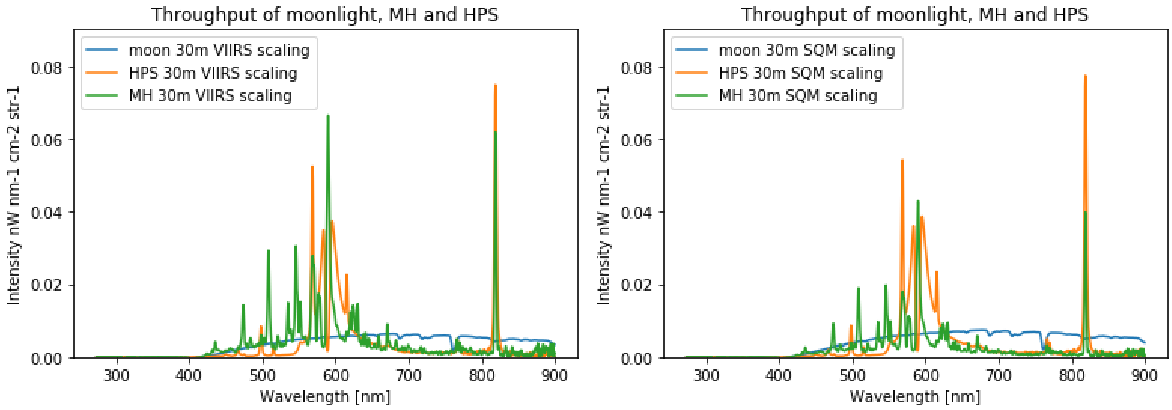

Figure 32: Throughput of spectral compositions of metal halide and high pressure sodium compared to moonlight scaled down with the VIIRS scaling factor (left) & SQM scaling factor (right)

In the case of metal halide and high pressure sodium light sources the higher peaks in the blue and green range when compared to moonlight, again suggest a disruptive effect on the settlement selection of the larvae of the blue mussel and specific oyster could occur. However, the high peak in the infrared range could potentially negate this disruption as it has been observed that red and near infrared colours induce settlement rates [Kim 2017, et al]. To what extent is difficult to determine as in Figure 10 it is shown that red wavelength ranges get absorbed as one goes further down. Also, the spectral composition of the metal halide and high pressure sodium is not smooth. One would have to know the spectral response of the blue mussel and pacific oyster to be able to determine whether these types of light would have the ecological effects as research suggests. With no smooth spectral composition the method used to compare the different sources of ALAN also becomes more unreliable. It can therefore not be stated whether the use of metal halide or high pressure sodium is better or worse than a LED light with this method. What can be stated is that the peaks of the spectral composition of the metal halide and high pressure sodium are of higher intensity compared to moonlight when penetrating coastal water. And are therefore expected to be more ecologically disruptive than natural moonlight.

Future research should develop and make use of more precise underwater models to properly determine whether the known effects of ALAN actually affect the Wadden Sea blue mussel and pacific oyster beds.

In summary, ALAN can be the cause for larvae of blue mussels and pacific oysters to select suboptimal zones to settle. Reducing the survival and reproduction success. In post-larvae stage blue mussels and pacific oysters are suggested to still have light sensitive features. ALAN is shown to be able to impact the growth of the blue mussel and may be influential for the mussels' health. Pacific oysters are suggested to have a light sensitive predator-avoidance ability and indirectly ALAN may cause a locally reduced availability of pacific oyster biomass. Overall, ALAN, in combination with other ecological stressors might alter, maybe even cause degradation of blue mussel and pacific oyster beds in the Wadden Sea [Rich 2006, et al]. Though little research towards the current state and impact of ALAN on the blue mussel and pacific oyster beds in the Wadden Sea is available, it can well be assumed that artificial light sources are an ecological stressor for the reefs in the tidal habitats of the Wadden Sea.

Blue mussels and pacific oysters	Effect	Consequence	Source
Light as a resource	Blue mussels growth rate signifcantly greater in darkness	Smaller mussels -> reduced availability of biomass	Strömgren 1976, et al; Trevelyan 1987, et al
Light as an information source	Light, wavelenght sensitive settlement selection altered for larvae	Suboptimal settlement selection which may reduce survival and reproduction succes	Davies 2013, et al; Kim 2021, et al; Mundy 1998, et al
	Pacific oyster shell opening light sensitive	Increased vulnerability to predators	Wu 2015, et al
	Disruption of circadian rhythm	Speculative	Robson 2010, et al

Figure 33: Summary of known and studied ecological effects of light pollution on blue mussels and pacific oysters

3.4 Primary and secondary producers

Primary producers are the basis for any food web and consist of photosynthetic algae, bacteria and plants . They are only found in the upper water levels and are essential for the production of carbon based biomass on which the secondary producers feed [waddensea-worldheritage.org]. A trace on carbon flows in the wadden sea has concluded that the secondary producers mainly depend on primary producers such as floating phytoplankton and immobile microalgae [Van Oevelen 2006, et al]. Since primary producers use light as an energy source it can be expected that artificial light is actually beneficial for the phytoplankton and algae. A recent study suggests that this is indeed the case [Diamantopoulou 2021, et al]. Green algae and an assemblage of diatom species were exposed to artificial light of different colours. Red, green and white. Contrary to the hypothesis that artificial white light would result in the highest algae growth, artificial green light was actually determined to cause the algae to grow the fastest [Diamantopoulou 2021, et al]. Overall, the study concludes that all ALAN wavelengths tested affected the biomass and diversity of phytoplankton, with red and green having the strongest effect [Diamantopoulou 2021, et al]. Another study found that for four species of phytoplankton, blue light also induces higher growth rates, close to 2 folds, compared to white light. [Gorai 2014, et al]. Though artificial light is found to increase the abundance of phytoplankton, the effect is not entirely positive. Excessive phytoplankton growth of particular species are known to cause harmful algae blooms, stripping the water of oxygen and subsequently causing mortality to other aquatic organisms [Diamantopoulou 2021, et al].

3.4.1 Diel vertical migration

Secondary producers are organisms that feed on plantlike material and are responsible for the carbon flow [Krop-Benesch 2022, et al]. They do so by ascending to the surface at dusk and delving back to deeper water levels at dawn. This process is known as diel vertical migration and is probably the largest daily migration of biomass in the world [Davies 2013, et al; Ludvigsen 2018, et al]. The migration has been observed for microscopic organisms such as zooplankton, up to species of large fish [Hays 2003, et al]. Diel vertical migration presumably results from a predator-avoidance mechanism during lighted conditions and is suggested to be heavily influenced by light levels [Longcore 2004, et al; Rich 2006, et al]. Light dimmer than that of a half moon ($< 10^{-1}$ lux) is sufficient to influence vertical migration and the vertical distribution of invertebrate secondary producer communities (zooplankton) [Garratt 2019, et al; Longcore 2004, et al]. A study in the unpolluted light environment in the high Arctic also concludes that the vertical migration of zooplankton is intimately connected to the light regime. They determined that measurements even under dim-light conditions would result in abundance estimates of zooplankton to be lower than reality [Ludvigsen 2018, et al]. [Moore 2000, et al] studied the effects of ALAN on a specific species of zooplankton called Daphnia and found that artificial light caused by urban skyglow reduces the amplitude and magnitude of the diel vertical migration of the species. A suppression of the diel vertical migration of zooplankton can be assumed to have detrimental effects on ecosystems like the Wadden Sea [Longcore 2004, et al; Rich 2006, et al]. Fewer zooplankton migrating to the water surface levels to feed could increase the primary producer populations, which in turn could, again, result in an algae bloom [Moore 2000, et al]. Disruption of diel vertical migration is also most likely to reduce carbon and nutrient flow to the lower water levels [Moore 2000, et al;Rich 2006, et al].

*Figure 34: Zooplankton [*available on:https://www.waddenvereniging.nl/waddengebied/voedselketen*]*

3.4.2 Analysis

A study towards phytoplankton dynamics conducted on several Wadden Sea sites has concluded that light is indeed a factor for phytoplankton growth [Van Beusekom 2019, et al]. However, the study mentions a decline in phytoplankton populations and actually lists an absence of light as one of the limiting factors. The most prominent factor suggested is zooplankton grazing. It has been shown that phytoplankton growth rates and microzooplankton grazing are tightly coupled [Van Beusekom 2017, et al], however not enough convincing evidence of an increasing grazing pressure exists to support the declining trend of phytoplankton observed [Van Beusekom 2019, et al]. More importantly, an overall decline in zooplankton densities in the Wadden Sea has actually been observed over the recent years [Boersma 2015, et al]. The reason suggested is a decrease of nutrients in the water.

For the assessments of the 5 ALAN sources analysed in coastal water for primary and invertebrate secondary producers Figures 29, 30,31 and 32 are again reviewed. In Figure 32 the comparison is made between metal halide, high pressure sodium or moonlight being the sole source of the brightness measurement at Lauwersoog [Vulto 2021], and the throughput to 30m of water depth is presented. Regarding primary producers, [Diamantopoulou 2021, et al] determined that green and red wavelengths induce higher abundance and diversity in algae assemblages. Metal halide and high pressure sodium lighting could thus have an impact on this physiological effect as they have high intensity peaks in the green and red range relative to natural moonlight, even still at 30m depth. Also according to Figure 10 of the NOAA, green wavelengths penetrate coastal water the furthest, which is also the colour that induced the highest abundance and diversity of the phytoplankton species [Diamantopoulou 2021, et al]. Another source of ALAN that is abundant in green wavelengths such as the LED in Figure 29 is also shown to have higher intensity in the green range relative to moonlight at 30m depth. Even more so, the blue range of the LED still reaches 30m of water depth in contrast to moonlight. It is known for four species of phytoplankton that blue light also induces higher growth rates compared to white light [Gorai 2014, et al].

In the case of invertebrate secondary producers (zooplankton) it can be determined that nearly all types of ALAN sources analysed can result in suppression of diel vertical migration. Looking at Figures 29, 30, 31 and 32, with the exception of the incandescent and halogen light source scaled down to the VIIRS brightness reference, all the sources of ALAN have a higher intensity for most of the wavelength ranges than that of the moon at 30m depth. Light dimmer than 10^{-1} lux is sufficient to alter the vertical distribution for zooplankton [Garratt 2019, et al; Longcore 2004, et al]. The brightness reference used in the analysis at Lauwersoog does not reach this illuminance level, however this reference is an observation of a single night, 17th April 2021 [Vulto 2021]. On a different (brighter) night or at different sites in the Wadden Sea the moon can reach these illuminance levels. And since Figures 29, 30, 31 and 32 show that for most ALAN sources the peaks can reach higher intensities at certain wavelengths at 30m depth then moonlight it can well be assumed that the presence of ALAN sources will suppress diel vertical migration.

Future research should clarify if ALAN can be attributed as one of the sources of the decline of zooplankton densities, or if it indeed alters the behaviour regarding diel vertical migration in the Wadden Sea. Furthermore, phytoplankton population trend research should be conducted near light-polluted and non light-polluted areas in the Wadden Sea to deduce whether ALAN actually increases phytoplankton abundance as research suggests.

In summary, ALAN is associated with potential health risks for the Wadden Sea's ecosystem on a primary and secondary producer level. ALAN is shown to be able to change primary producer abundance and zooplankton migration behaviour. Potentially altering the biomass availability and distribution on the surface and deeper water levels. Such a change could disrupt behaviour, rhythm and population levels for the entire Wadden Sea's marine ecosystem and fundamentally change the marine food web.

Primary and secondary producers	Effect	Consequence	Source
Light as a resource	Artifical light increases phytoplankton abundance and diversity	Harmful algae blooms	Diamantopoulou 2021, et al
Light as an information source	Zooplankton diel vertical migration is supressed	Reduction of carbon and nutrient transport, fewer zooplankton migration to water surface	Longcore 2004, et al; Moore 2000, et al; Rich 2006, et al

Figure 35: Summary of known and studied effects of light pollution on primary and invertebrate secondary producers

3.5 Preserve & conserve

The Wadden Sea's ecosystem is under threat from environmental stressors such as global climate change, water pollution, invasive alien species and human activities [Krop-Benesch 2022, et al]. Light pollution has been shown to be one of these stressors and can be harmful on its own, but can also in combination with other stressors exponentially increase the pressure on the tidal ecosystem [Gaston 2013, et al]. The impact ALAN has on the tidal flats ranges further than is treated in this report as other research suggests that ALAN also negatively impacts larger secondary producers like fish in behaviour, physiologically and reproduction success [Brüning 2010, et al; Brüning 2018, et al; Grubisic 2019, et al; Krop-Benesch 2022, et al]. Insects for example are also influenced by artificial light sources of which the most prominent example is the attraction to light [Gaston 2013, et al]. This attraction can draw insects from their habitat, reducing population sizes and negatively impact their role in the food web or as a pollinator [Gaston 2013, et al; Sullivan 2018, et al].

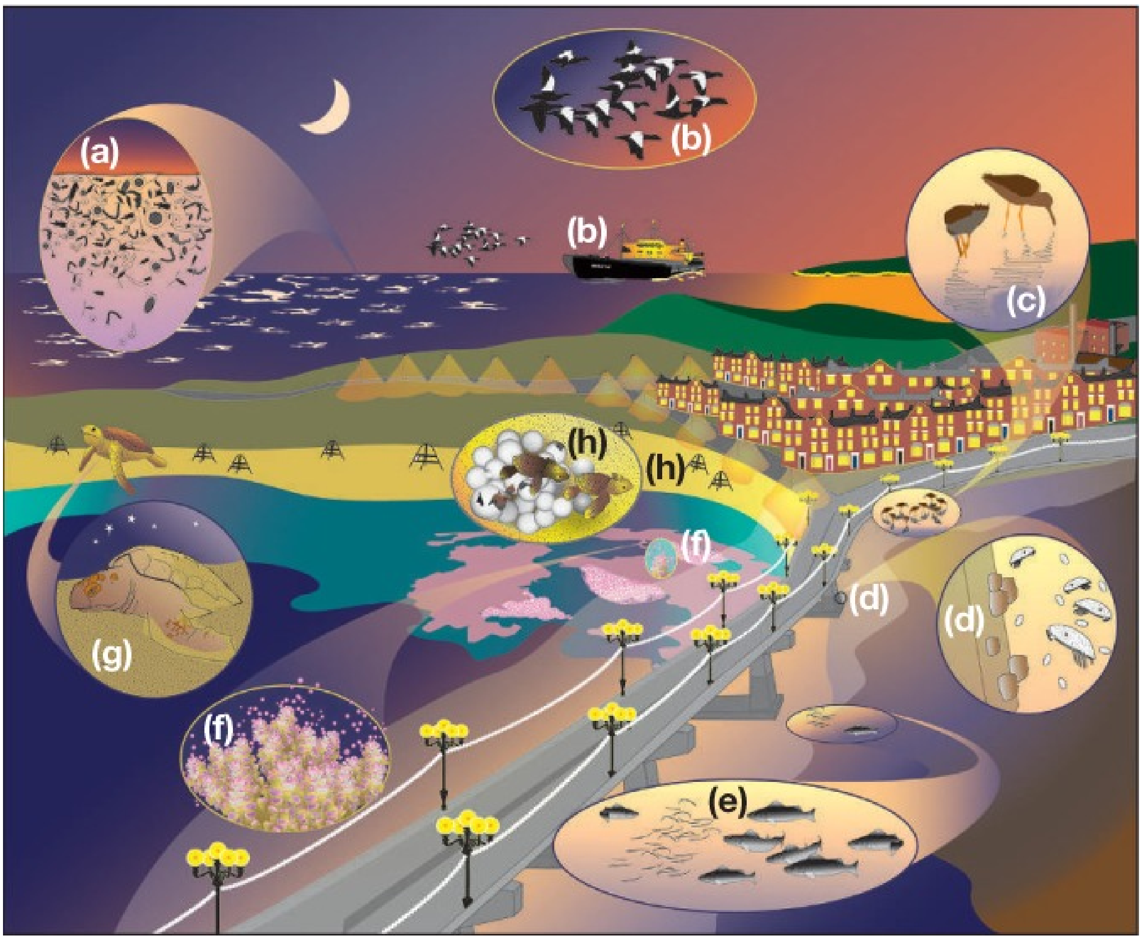

Figure 36: Diagram of some known impacts of ALAN on marine ecosystems. (a) Suppressions of the diel vertical migration of zooplankton. (b) Bird collisions with lit-up vessels or structures. (c) Extended activity time of foraging shorebirds. (d) Suboptimal settlement selection for mussel and oyster larvae. (e) Aggregation of fish due to light attraction leads to local intensified predation. (f) De-synchronization from lunar phase for coral (not relevant for Wadden Sea). (g&h) Displacement of nesting sea turtles and disorientation of turtle hatchlings (not relevant for the Wadden Sea) [Davies 2013, et al]

3.5.1 Applications

The preservation of the natural dark sky is of great importance for the function of the Wadden Sea's unique ecosystem. The most obvious is to shut off the lights at night. However this may be met with resilience as nighttime lighting is often associated with people's safety [Krop-Benesch 2022, et al]. Though some studies provide some positive effects regarding increased safety of nighttime lighting, these are more emphasised on the pedestrians feeling of safety [Portnov 2020, et al]. Even if the nighttime lighting is deemed necessary, for example for work or security, much of the light can still be wasteful by not directly illuminating the required area [Fotios 2018, et al]. Light shielding is often mentioned as a method to reduce light pollution [Longcore 2004, et al]. While from an astronomy point of view this does result in a darker sky measurement, shielded light can still be impactful in an ecological sense since downward pointed light shines on and propagates through the water surface in a coastal environment [Longcore 2004, et al]. Methods to reduce ecological consequences via precise testing and development of what light sources best to use could prove useful for terrestrial and marine ecosystems [Longcore 2018, et al]. Coupled with a greater understanding of ecological impacts of light pollution the use of nighttime lighting can be greatly improved in order to preserve the natural ecosystem of the Wadden Sea, as well as other marine or terrestrial environments.

Option	Biodiversity impact	Cost and carbon saving impact	Human security and amenity	Dark skies impact
Maintain natural unlit areas	0	0	0	0
Remove lighting to extend natural unlit areas	+	+	0/-	+
Reduce duration of lighting	0/+	+	0/-	+
Reduce trespass of light	+	+	+/0	+
Reduce intensity of light	+	+	+/0/-	+
Broaden spectrum of light	-	+	+	-

Figure 37: Proposed options for changing ALAN and their impacts relative to current practice. 0: no change; +: positive; -: negative [Gaston 2012, et al]

Currently the Wadden Sea is harbouring four certified Dark Sky Parks [available on: https://www.darksky.org/our-work/conservation/idsp/parks/]. At Lauwersmeer and Boschplaat in The Netherlands and Spiekeroog and Pellworm in Germany. The installation of these Dark Sky Places are, considering the reach of light pollution emissions, not large enough and are not ecologically optimal since they are spaced quite a distance from each other [Krop-Benesch 2022, et al]. In an ecological sense, a Dark Sky Conservation Park spanning the entire Wadden Sea World Heritage area would be an astronomical conservation achievement.

4. Discussion & Conclusion

In this work the loss of natural darkness and the ecological implications of which were reviewed for the Wadden Sea, an UNESCO World Heritage site. The dark sky maps reviewed computed their results using the VIIRS instrument data and SQM measurements [Falchi 2016, et al]. It is important to note that satellite data and SQM data do not immediately measure light emissions the way avian and marine species would perceive them [Katz 2016, et al]. Firstly, biological effects of light are strongly dependent on the light spectrum [Salvador 2018, et al]. Some species react stronger or differently depending on which wavelength is emitted. For example green light induces algae growth [Diamantopoulou 2021, et al] while disrupting mussel and oyster larvae settlement selection [Kim 2021, et al]. SQM or satellite measurements however, have no detailed information of the composition of the light it measures [Salvador 2018, et alworldview.earthdata.nasa.gov]. The world atlas computed by P. Cinzano also makes a series of constant assumptions in their model [Falchi 2016, et al]. The maps were computed assuming a clear night sky, the spectral composition of the ALAN sources were assumed to be identical and for cities an upward emission function was computed [Falchi 2016, et al]. Any deviation from these assumptions would result in a less accurate display of ALAN for a given region. The atmospheric condition is the most prominent deviation since a small increase in aerosols in the sky can result in higher light pollution near and inside urban areas and with an overcast sky a several fold increase in the form of sky glow can be expected in the surrounding area according to [Falchi 2016, et al]. The ecological consequences therefore can be larger than one might assume by looking at ALAN levels computed for clear night skies, as is the case with the maps reviewed in this report. Nevertheless, the maps clearly show an exposure of artificial nighttime lighting affecting the Wadden Sea World Heritage area.

For the assessment of different types of ALAN sources scattered in coastal water only light scattering in water was taken into account and not the absorption of water. Also the scattering was assumed to be proportional to Rayleigh scattering. The Rayleigh scattering was assumed to be proportional to only water depth and wavelength as parameters. In reality the actual scattering of light might deviate from these assumptions as for example salinity of the water might affect the scattering efficiency. Nevertheless, in light of these assumptions, LED's have been shown to be able to be a stressor for blue mussel and pacific oyster larvae. Since the blue wavelengths of the light source are of such high intensity that till 30m of coastal water depth not all blue light is scattered away, in contrast to natural moonlight. Blue light is presumed to have the largest overall ecological impact on marine (and avain) species [Longcore 2018, et al]. It has been shown that the VIIRS does not observe the blue wavelength range, so the negative effects associated with blue light can not be assessed using the VIIRS only. The same reasoning for light scattering is presented for metal halide and high pressure sodium light sources. Peaks of blue and most prominently green are of higher intensity at 30m water depth compared to moonlight. LED's, metal halide and high pressure sodium light sources are also shown to be able to induce higher abundance and diversity of phytoplankton compared to moonlight. As the same reasoning can be applied that not all blue and green light is scattered away at 30m of water depth. So in local instances where the emitted light source is bright enough as tested in the literature [Diamantopoulou 2021, et al; Gorai 2014, et al] it will have ecological implications for the phytoplankton population and subsequently the health of the water.

Diel vertical migration for zooplankton is shown to be able to be suppressed by all types of ALAN sources analysed as an illumination of less than $< 10^{-1}$ lux is sufficient to alter the vertical distribution of zooplankton [Garratt 2019, et al; Longcore 2004, et al]. Compared to moonlight, LED's, metal halide and high pressure sodium are expected to reach these illumination levels sooner as their peaks are of higher intensity when propagating through water depth. Incandescent and halogen light sources have a spectral composition similar to that of the moon, but are still expected to suppress vertical migration in areas where their use is bright enough.

Another limitation to this study is that there exist various research papers regarding the topic of how avian and marine species react to artificial light exposure, however not all studies distinguish between different wavelengths [Health Council of the Netherlands 2000]. And the units in which the lighting sources studied are presented do not always correspond with each other. Sometimes the intensity is given in lux [Trevelyan 1987, et al], while other times irradiance units are presented [Strömgren 1976, et al]. The fluctuations in presented results made it sometimes tedious to determine whether the results would actually be of relevance for the case of ALAN exposure in the Wadden Sea. To better quantify the effects light pollution has on the Wadden Sea's ecosystem a universally adopted method of study relating to nighttime exposure effects on marine and avian species should be implemented. As well as a three dimensional model of ALAN emission spanning the Wadden Sea World Heritage area. Future studies should examine ALAN emissions by further developing and combining SQM measurements, Satellite data and computer models. A focus on quantifying different wavelengths emitted by artificial light sources in the Wadden Sea should also further boost our understanding of the current ecological impact of nighttime lighting [Katz 2016, et al]. Furthermore, modelling ALAN emissions in the atmosphere can be challenging, but for marine environments modelling light emissions propagating through the water surface and underwater is even more rigorous [Prabhakaran 2018, et al]. Because of all this it is only possible to conclude that ALAN is currently an ecological stressor, and actions should be taken to clarify whether avian and marine species are as affected as research suggests.

Nevertheless, this report has shown that artificial light at night can be an ecological stressor for the Wadden Sea World Heritage area. Ecological light pollution can, together with other environmental stressors such as climate change, put a tremendous strain on the longevity of the Wadden Sea's ecosystem. Whilst ALAN can have some positive effects for the individual animal, many negative effects at various levels of biological organisation are associated with nighttime lighting. Ecological light pollution is shown to be a serious stressor for marine and avian population levels and potentially the functioning of the Wadden Sea's ecosystem. ALAN alters biological rhythms, influencing marine and avian species on a sensory and physiological level and disrupts natural rhythms by creating eternal full moon scenarios. The exposure of ALAN in the Wadden Sea has between 2014 and 2020 only increased for most parts in the UNESCO World Heritage area, according to the world atlas model. Models for artificial sky brightness are limited by the current measurement techniques to quantify the loss of darkness and subject to assumptions to be able to be computed. Nonetheless it can be concluded that the Wadden Sea is losing its natural darkness, the consequences are shown to not only be constrained to the Wadden Sea's ecosystem, but can influence ecosystem populations on a global scale.

The ecological use of nighttime lighting is only recently being researched and the application of which is not yet being implemented. Recommendations for reducing light pollution are not all beneficial in an ecological sense. Emitting different wavelengths can be beneficial to some species, while negatively impacting others. For example it has been suggested that artificial light sources should be reduced in blue content and shifted towards the longer wavelengths. The metric from [Longcore 2018, et al] suggests filtered yellow-green and amber coloured LEDs are to have the least effects on marine and terrestrial wildlife. However in this report it has been shown that these wavelengths do too have ecological consequences such as mussel and oyster larvae settling in suboptimal zones. The preservation of darkness in the Wadden Sea is a tremendous challenge, but with better astronomical measurement techniques, computer simulated models of light pollution and further developed understanding of ALAN on marine and avian species, the task is not impossible.

Just recently, the Keep It Dark (KID) project led by Rijksuniversiteit Groningen has been approved and received funding to further tackle light pollution in the Wadden Sea (North Sea) area [available on https://northsearegion.eu/about-the-programme/programme-news/first-approvals-in-the-new-programme/] The project aims to develop a joint monitoring system of ALAN in the North Sea. This report aims to be beneficial to the KID project and other initiatives to preserve and conserve the Wadden Sea in regard to light pollution.

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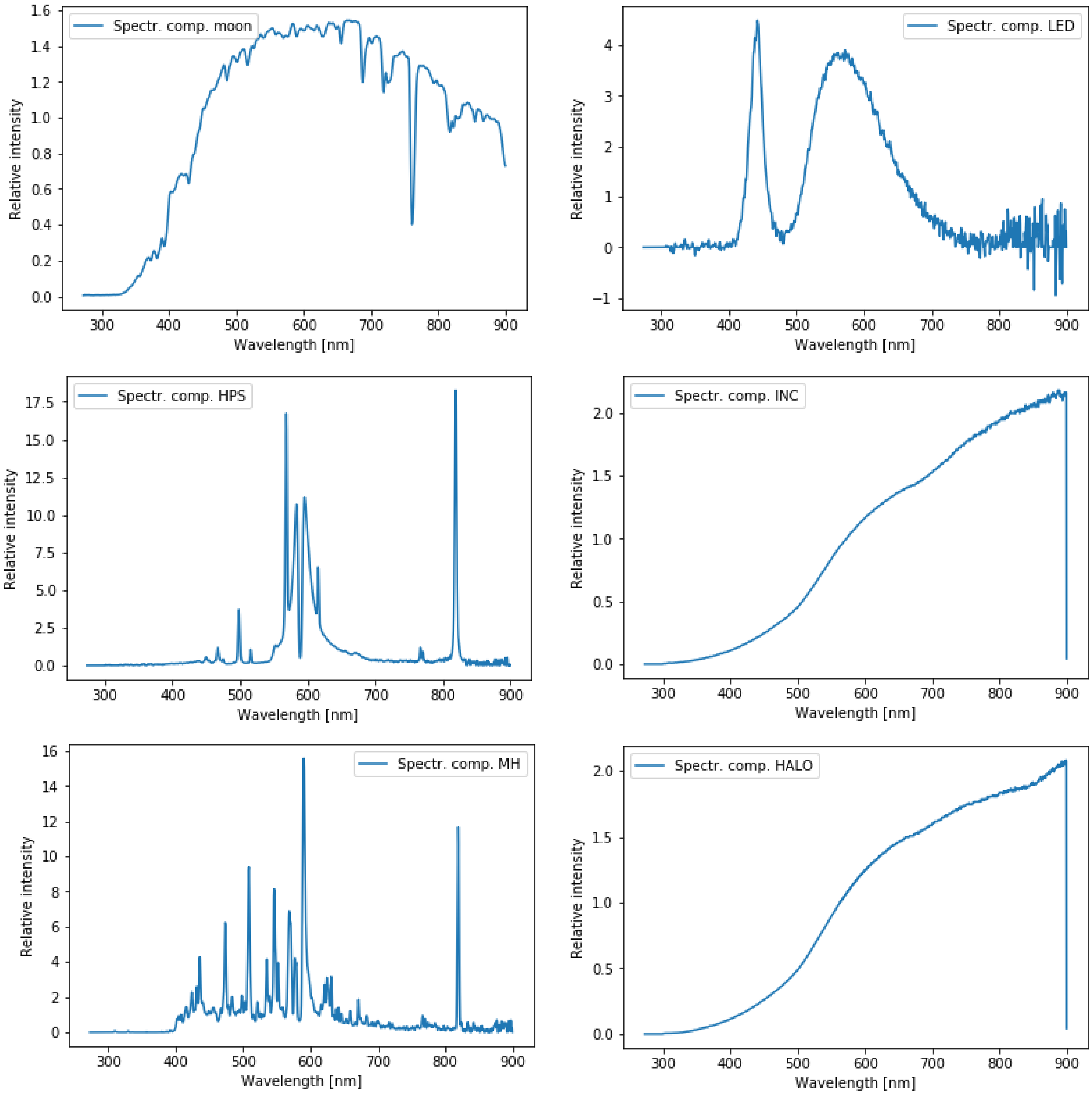
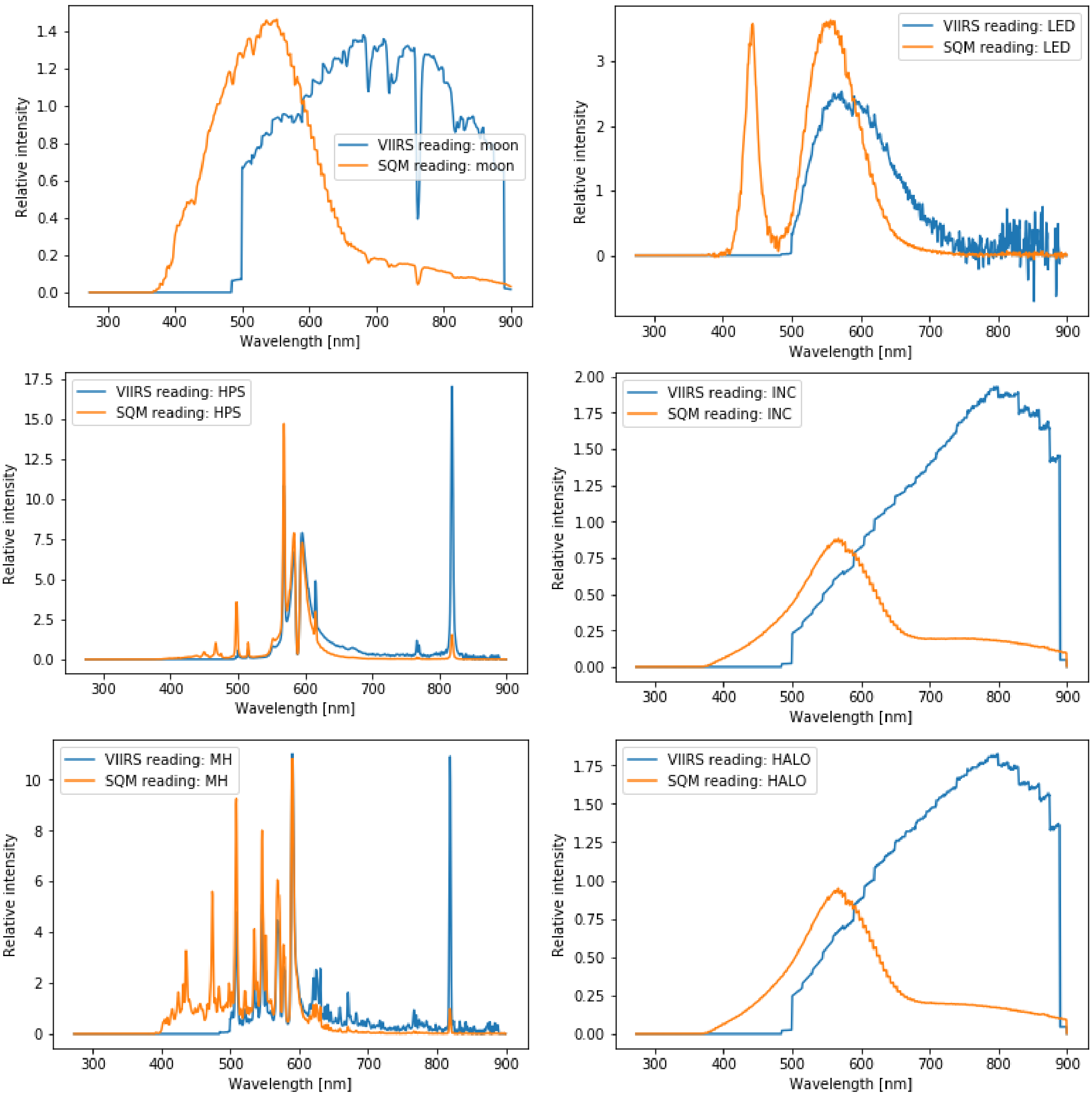
Appendix

Graphs



Spectral compositions of all the light sources analysed



VIIRS & SQM reading of all the spectral compositions

Code

```
import numpy as np
import pandas as pd
from matplotlib import pyplot as plt
import spectres
import scipy.integrate as Int

x = pd.read_fwf("DNB_RSR.txt")
x.to_csv("DNB_RSR.csv")

data = pd.read_csv("DNB_RSR.csv") #spectral response DNB VIIRS
speccomps = pd.read_csv("Spectralcomps.csv") #spectral compositions sunlight & artificial
specdatabase = pd.read_csv("SpectralDatabase.csv") #spectral power distribution database of
artificial LED sources
moon = pd.read_csv("MoonSpectrum.csv") #spectral composition of moonlight
SQM = pd.read_csv("SQMresponse.csv")

data = data.iloc[1: , :] #get rid of first non-numerical row
specdatabase = specdatabase.iloc[1:, :]
data = data.rename(columns = {"Unnamed: 2":"Wavelength", "Unnamed: 3":"RSR"}) #rename
column headers

#change to floats
data["Wavelength"] = data["Wavelength"].astype(float)
data["RSR"] = data["RSR"].astype(float)

moon["Wavelength"] = moon["Wavelength"].astype(float)
moon["RI"] = moon["RI"].astype(float)

SQM["Wavelength"] = SQM["Wavelength"].astype(float)
SQM["intrel"] = SQM["intrel"].astype(float)

#viirs = data.plot(kind="scatter", x="Wavelength", y="RSR")

#sun = speccomps.plot(kind="line", x="Sunlight", y="RI")
#LED = speccomps.plot(kind="line", x="LED Philips RoadStar-GPLS-49 LED Streetlight",
y="RI.1")
#HPS = speccomps.plot(kind="line", x="HPS Philips Helios Streetlight", y="RI.2")
#INC = speccomps.plot(kind="line", x="INC Sylvania A21 Domestic", y="RI.3")
#MH = speccomps.plot(kind="line", x="MH Philips - Industrial", y="RI.4")
#HALO = speccomps.plot(kind="line", x="HALO Globe BR30 Domestic", y="RI.5")

#convert to np array
new_wave = np.asarray(speccomps["Sunlight"])
spec_wavs = np.asarray(data["Wavelength"])
spec_fluxes = np.asarray(data["RSR"])
moon_wavs = np.asarray(moon["Wavelength"])
spec_moon = np.asarray(moon["RI"])

#get values for same wavelength axis
newviirs = spectres.spectres(new_wave,spec_wavs,spec_fluxes,fill=0)
newmoon = spectres.spectres(new_wave,moon_wavs,spec_moon,fill=0)
newSQM =
spectres.spectres(new_wave,np.asarray(SQM["Wavelength"]),np.asarray(SQM["intrel"]), fill=0)
```

```
#viirs & SQM response of speccomps
speccomps_RI = np.asarray(speccomps["RI"])
viirs_sun = newviirs * speccomps_RI
SQM_sun = newSQM * speccomps_RI

newmoon = newmoon/np.mean(newmoon)
viirs_moon = newviirs * newmoon
SQM_moon = newSQM * newmoon


LED_RI = np.asarray(speccomps["RI.1"])
LED_RI = LED_RI/np.mean(LED_RI)
viirs_LED = newviirs * LED_RI
SQM_LED = newSQM * LED_RI

HPS_RI = np.asarray(speccomps["RI.2"])
HPS_RI = HPS_RI/np.mean(HPS_RI)
viirs_HPS = newviirs * HPS_RI
SQM_HPS = newSQM * HPS_RI

INC_RI = np.asarray(speccomps["RI.3"])
INC_RI = INC_RI/np.mean(INC_RI)
viirs_INC = newviirs * INC_RI
SQM_INC = newSQM * INC_RI

MH_RI = np.asarray(speccomps["RI.4"])
MH_RI = MH_RI/np.mean(MH_RI)
viirs_MH = newviirs * MH_RI
SQM_MH = newSQM * MH_RI

HALO_RI = np.asarray(speccomps["RI.5"])
HALO_RI = HALO_RI/np.mean(HALO_RI)
viirs_HALO = newviirs * HALO_RI
SQM_HALO = newSQM * HALO_RI

#plt.plot(new_wave, speccomps_RI/np.max(speccomps_RI))
#plt.plot(new_wave, newmoon,label="Spectr. comp. moon")
#plt.plot(new_wave,newviirs,label="VIIRS spectral response")
#plt.plot(new_wave,newSQM,label= "SQM spectral response")

#plt.plot(new_wave,LED_RI,label="Spectr. comp. LED")
#plt.plot(new_wave,HPS_RI,label="Spectr. comp. HPS")
#plt.plot(new_wave,INC_RI,label="Spectr. comp. INC")
#plt.plot(new_wave,MH_RI,label="Spectr. comp. MH")
#plt.plot(new_wave,HALO_RI,label="Spectr. comp. HALO")

#plt.plot(new_wave, viirs_sun/np.max(viirs_sun))
#plt.plot(new_wave, viirs_moon,label="VIIRS reading: moon")
#plt.plot(new_wave, viirs_LED,label="VIIRS reading: LED")
#plt.plot(new_wave, viirs_HPS,label="VIIRS reading: HPS")
#plt.plot(new_wave, viirs_INC,label="VIIRS reading: INC")
#plt.plot(new_wave, viirs_MH,label="VIIRS reading: MH")
#plt.plot(new_wave, viirs_HALO,label="VIIRS reading: HALO")

#plt.plot(new_wave, SQM_sun/np.max(SQM_sun))
#plt.plot(new_wave, SQM_moon,label="SQM reading: moon")
```

```
#plt.plot(new_wave, SQM_LED,label="SQM reading: LED")
#plt.plot(new_wave, SQM_HPS,label="SQM reading: HPS")
#plt.plot(new_wave, SQM_INC,label="SQM reading: INC")
#plt.plot(new_wave, SQM_MH,label="SQM reading: MH")
#plt.plot(new_wave, SQM_HALO,label="SQM reading: HALO")

unitconv = 1.464128843338821e-1 #conversion factor 1 mcd m-2 = 1.46 *10^-1 nW cm-2 str-1

lauwSQM = 1.08e8 * 10**(-0.4*21.72) #darkest 10% of lauwersoog in mcd m-2 (credit lasse)
lauwviirs = 1.9474509803392157 #nW cm-2 str-1 (credit lasse)
print("Lauwersoog from viirs:",lauwviirs,"[nW cm-2 str-1]")
print("Darkest 10% of Lauwersoog from SQM:",lauwSQM, "[mcd
m-2]","->",lauwSQM/unitconv,"[nW cm-2 str-1]")


def Integral(y,x):
   return Int.simps(y,x)

#integral of emission spectra
INT_viirs_moon = Integral(viirs_moon,new_wave)
INT_SQM_moon = Integral(SQM_moon,new_wave)

INT_viirs_LED = Integral(viirs_LED,new_wave)
INT_SQM_LED = Integral(SQM_LED,new_wave)

INT_viirs_HPS = Integral(viirs_HPS,new_wave)
INT_SQM_HPS = Integral(SQM_HPS, new_wave)

INT_viirs_INC = Integral(viirs_INC,new_wave)
INT_SQM_INC = Integral(SQM_INC,new_wave)

INT_viirs_MH = Integral(viirs_MH,new_wave)
INT_SQM_MH = Integral(SQM_MH,new_wave)

INT_viirs_HALO = Integral(viirs_HALO,new_wave)
INT_SQM_HALO = Integral(SQM_HALO,new_wave)

def scaling(bright1, bright2):
   return bright2/bright1

#scaling factor for each emission
viirs_scaling_moon = scaling(INT_viirs_moon,lauwviirs)
SQM_scaling_moon = scaling(INT_SQM_moon,lauwSQM/unitconv)

viirs_scaling_LED = scaling(INT_viirs_LED,lauwviirs)
SQM_scaling_LED = scaling(INT_SQM_LED, lauwSQM/unitconv)

viirs_scaling_HPS = scaling(INT_viirs_HPS,lauwviirs)
SQM_scaling_HPS = scaling(INT_SQM_HPS,lauwSQM/unitconv)

viirs_scaling_INC = scaling(INT_viirs_INC,lauwviirs)
SQM_scaling_INC = scaling(INT_SQM_INC,lauwSQM/unitconv)

viirs_scaling_MH = scaling(INT_viirs_MH,lauwviirs)
SQM_scaling_MH = scaling(INT_SQM_MH,lauwSQM/unitconv)
```

```
viirs_scaling_HALO = scaling(INT_viirs_HALO,lauwviirs)
SQM_scaling_HALO = scaling(INT_SQM_HALO,lauwSQM/unitconv)

print("")
print("VIIRS scaling for moon:",viirs_scaling_moon,"| SQM scaling for
moon:",SQM_scaling_moon)
print("VIIRS scaling for LED:",viirs_scaling_LED,"| SQM scaling for LED:",SQM_scaling_LED)
print("VIIRS scaling for HPS:",viirs_scaling_HPS,"| SQM scaling for HPS:",SQM_scaling_HPS)
print("VIIRS scaling for INC:",viirs_scaling_INC,"| SQM scaling for INC:",SQM_scaling_INC)
print("VIIRS scaling for MH:",viirs_scaling_MH,"| SQM scaling for MH:",SQM_scaling_MH)
print("VIIRS scaling for HALO:",viirs_scaling_HALO,"| SQM scaling for
HALO:",SQM_scaling_HALO)

plt.xlabel("Wavelength [nm]")
plt.ylabel("Relative intensity")
plt.legend()
plt.show()
```

```
unitconv = 1.464128843338821e-1 #conversion factor 1 mcd m-2 = 1.46 *10^-1 nW cm-2 str-1

#scale factor difference between viirs and SQM
def diffscalefactor(scaleviirs,scaleSQM):
   return scaleviirs - scaleSQM

#scale factor difference for all spectral sources
Moon_scale_diff = diffscalefactor(viirs_scaling_moon,SQM_scaling_moon)
LED_scale_diff = diffscalefactor(viirs_scaling_LED,SQM_scaling_LED)
HPS_scale_diff = diffscalefactor(viirs_scaling_HPS,SQM_scaling_HPS)
INC_scale_diff = diffscalefactor(viirs_scaling_INC,SQM_scaling_INC)
MH_scale_diff = diffscalefactor(viirs_scaling_MH,SQM_scaling_MH)
HALO_scale_diff = diffscalefactor(viirs_scaling_HALO,SQM_scaling_HALO)

print("Difference in scaling factor VIIRS-SQM")
print("Moon:",Moon_scale_diff)
print("LED:",LED_scale_diff)
print("HPS:",HPS_scale_diff)
print("INC:",INC_scale_diff)
print("MH:",MH_scale_diff)
print("HALO:",HALO_scale_diff)

ScalingDiff =
np.array([Moon_scale_diff,LED_scale_diff,HPS_scale_diff,INC_scale_diff,MH_scale_diff,HA
LO_scale_diff])

#scaling what viirs & SQM observe to how much is needed to fully contribute
Scaled_viirs_LED = viirs_LED * viirs_scaling_LED
Scaled_SQM_LED = SQM_LED * SQM_scaling_LED

Scaled_viirs_HPS = viirs_HPS * viirs_scaling_HPS
Scaled_SQM_HPS = SQM_HPS * SQM_scaling_HPS

Scaled_viirs_INC = viirs_INC * viirs_scaling_INC
Scaled_SQM_INC = SQM_INC * SQM_scaling_INC

Scaled_viirs_MH = viirs_MH * viirs_scaling_MH
Scaled_SQM_MH = SQM_MH * SQM_scaling_MH
```

```
Scaled_viirs_HALO = viirs_HALO * viirs_scaling_HALO
Scaled_SQM_HALO = SQM_HALO * SQM_scaling_HALO


plt.plot(new_wave,Scaled_viirs_LED,label="VIIRS reading LED Scaled")
#plt.plot(new_wave,Scaled_viirs_HPS,label="VIIRS reading HPS Scaled")
#plt.plot(new_wave,Scaled_viirs_INC,label="VIIRS reading INC Scaled")
#plt.plot(new_wave,Scaled_viirs_MH,label="VIIRS reading MHScaled")
#plt.plot(new_wave,Scaled_viirs_HALO,label="VIIRS reading HALO Scaled")

plt.plot(new_wave,Scaled_SQM_LED,label="SQM reading LED Scaled")
#plt.plot(new_wave,Scaled_SQM_HPS,label="SQM reading HPS Scaled")
#plt.plot(new_wave,Scaled_SQM_INC,label="SQM reading INC Scaled")
#plt.plot(new_wave,Scaled_SQM_MH,label="SQM reading MH Scaled")
#plt.plot(new_wave,Scaled_SQM_HALO,label="SQM reading HALO Scaled")

#original spectra if ever usefull
ORIG_moon = spectres.spectres(new_wave,moon_wavs,spec_moon,fill=0)
ORIG_LED = np.asarray(speccomps["RI.1"])
ORIG_HPS = np.asarray(speccomps["RI.2"])
ORIG_INC = np.asarray(speccomps["RI.3"])
ORIG_MH = np.asarray(speccomps["RI.4"])
ORIG_HALO = np.asarray(speccomps["RI.5"])


plt.xlabel("Wavelength [nm]")
plt.ylabel("Intensity [nW nm-1 cm-2 str-1]")
plt.legend()
plt.title("Scaled reading VIIRS & SQM")
plt.show()
print("Area under VIIRS reading:",Integral(Scaled_viirs_LED,new_wave),"nW cm-2 str-1")
print("Area under SQM reading:",Integral(Scaled_SQM_LED,new_wave),"nW cm-2 str-1")
```

```
def Rayleigh_water(xi,yi,z):
   #d = 4901 #nm
   #n = 1.333 #refractive index
   #I = yi*(1/(2*(z**2)))*(((2*np.pi)/xi)**4)*(((n**2 -1)/(n**2 +2))**2)*((d/2)**6)
   IR = (yi*z)/(xi**4)
   return IR

#compute Rayleigh "scattering" at two different depths
moon_Ray = newmoon - Rayleigh_water(new_wave,newmoon,15e9)
moon_Ray2 = newmoon - Rayleigh_water(new_wave,newmoon,30e9)

LED_Ray = LED_RI - Rayleigh_water(new_wave,LED_RI,15e9)
LED_Ray2 = LED_RI - Rayleigh_water(new_wave, LED_RI,30e9)

HPS_Ray = HPS_RI - Rayleigh_water(new_wave, HPS_RI,15e9)
HPS_Ray2 = HPS_RI - Rayleigh_water(new_wave, HPS_RI,30e9)

INC_Ray = INC_RI - Rayleigh_water(new_wave, INC_RI,15e9)
INC_Ray2 = INC_RI - Rayleigh_water(new_wave, INC_RI,30e9)

MH_Ray = MH_RI - Rayleigh_water(new_wave, MH_RI,15e9)
MH_Ray2 = MH_RI - Rayleigh_water(new_wave, MH_RI,30e9)
```

```
HALO_Ray = HALO_RI - Rayleigh_water(new_wave, HALO_RI,15e9)
HALO_Ray2 = HALO_RI - Rayleigh_water(new_wave, HALO_RI,30e9)

#plotting what is not scattered at two different depths according to VIIRS scaling and SQM
scaling

plt.plot(new_wave,newmoon*viirs_scaling_moon,label="moon 0m VIIRS scaling")
#plt.plot(new_wave,moon_Ray*viirs_scaling_moon,label="moon 15m VIIRS scaling")
#plt.plot(new_wave,moon_Ray2*viirs_scaling_moon,label="moon 30m VIIRS scaling")
plt.plot(new_wave,newmoon*SQM_scaling_moon,label="moon 0m SQM scaling")
#plt.plot(new_wave,moon_Ray*SQM_scaling_moon,label="moon 15m SQM scaling")
#plt.plot(new_wave,moon_Ray2*SQM_scaling_moon,label="moon 30m SQM scaling")

#plt.plot(new_wave,LED_RI*viirs_scaling_LED,label="LED 0m VIIRS scaling")
#plt.plot(new_wave,LED_Ray*viirs_scaling_LED,label="LED 15m VIIRS scaling")
#plt.plot(new_wave,LED_Ray2*viirs_scaling_LED,label="LED 30m VIIRS scaling")
#plt.plot(new_wave,LED_RI*SQM_scaling_LED,label="LED 0m SQM scaling")
#plt.plot(new_wave,LED_Ray*SQM_scaling_LED,label="LED 15m SQM scaling")
#plt.plot(new_wave,LED_Ray2*SQM_scaling_LED, label="LED 30m SQM scaling")

#plt.plot(new_wave,HPS_RI*viirs_scaling_HPS,label="HPS 0m VIIRS scaling")
#plt.plot(new_wave,HPS_Ray*viirs_scaling_HPS,label="HPS 15m VIIRS scaling")
#plt.plot(new_wave,HPS_Ray2*viirs_scaling_HPS,label="HPS 30m VIIRS scaling")
#plt.plot(new_wave,HPS_RI*SQM_scaling_HPS,label="HPS 0m SQM scaling")
#plt.plot(new_wave,HPS_Ray*SQM_scaling_HPS,label="HPS 15m SQM scaling")
#plt.plot(new_wave,HPS_Ray2*SQM_scaling_HPS,label="HPS 30m SQM scaling")

#plt.plot(new_wave,INC_RI*viirs_scaling_INC,label="INC 0m VIIRS scaling")
#plt.plot(new_wave,INC_Ray*viirs_scaling_INC,label="INC 15m VIIRS scaling")
#plt.plot(new_wave,INC_Ray2*viirs_scaling_INC,label="INC 30m VIIRS scaling")
#plt.plot(new_wave,INC_RI*SQM_scaling_INC,label="INC 0m SQM scaling")
#plt.plot(new_wave,INC_Ray*SQM_scaling_INC,label="INC 15m SQM scaling")
#plt.plot(new_wave,INC_Ray2*SQM_scaling_INC,label="INC 30m SQM scaling")

#plt.plot(new_wave,MH_RI*viirs_scaling_MH,label="MH 0m VIIRS_scaling")
#plt.plot(new_wave,MH_Ray*viirs_scaling_MH,label="MH 15m VIIRS scaling")
#plt.plot(new_wave,MH_Ray2*viirs_scaling_MH,label="MH 30m VIIRS scaling")
#plt.plot(new_wave, MH_RI*SQM_scaling_MH,label="MH 0m SQM scaling")
#plt.plot(new_wave,MH_Ray*SQM_scaling_MH,label="MH 15m SQM scaling")
#plt.plot(new_wave,MH_Ray2*SQM_scaling_MH,label="MH 30m SQM scaling")

#plt.plot(new_wave,HALO_RI*viirs_scaling_HALO,label="HALO 0m VIIRS scaling")
#plt.plot(new_wave,HALO_Ray*viirs_scaling_HALO,label="HALO 15m VIIRS scaling")
#plt.plot(new_wave,HALO_Ray2*viirs_scaling_HALO,label="HALO 30m VIIRS scaling")
#plt.plot(new_wave,HALO_RI*SQM_scaling_HALO,label="HALO 0m SQM scaling")
#plt.plot(new_wave,HALO_Ray*SQM_scaling_HALO,label="HALO 15m SQM scaling")
#plt.plot(new_wave,HALO_Ray2*SQM_scaling_HALO,label="HALO 30m SQM scaling")

#plt.ylim([0,(INC_RI.max()+INC_RI.max()/50)*SQM_scaling_INC])

plt.title("Moonlight")
plt.ylabel("Intensity nW nm-1 cm-2 str-1")
plt.xlabel("Wavelength [nm]")
plt.legend()
plt.show()
```

```
print("Area under surface graph:",Integral(newmoon*viirs_scaling_moon,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth
graph:",Integral(moon_Ray*viirs_scaling_moon,new_wave),"[nW cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(moon_Ray2*viirs_scaling_moon,new_wave),"[nW cm-2 str-1]")
print("Area under surface graph:",Integral(newmoon*SQM_scaling_moon,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth
graph:",Integral(moon_Ray*SQM_scaling_moon,new_wave),"[nW cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(moon_Ray2*SQM_scaling_moon,new_wave),"[nW cm-2 str-1]")

#print("Area under surface graph:",Integral(LED_RI*viirs_scaling_LED,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth graph:",Integral(LED_Ray*viirs_scaling_LED,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(LED_Ray2*viirs_scaling_LED,new_wave),"[nW cm-2 str-1]")
#print("Area under surface graph:",Integral(LED_RI*SQM_scaling_LED,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth graph:",Integral(LED_Ray*SQM_scaling_LED,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(LED_Ray2*SQM_scaling_LED,new_wave),"[nW cm-2 str-1]")

#print("Area under surface graph:",Integral(HPS_RI*viirs_scaling_HPS,new_wave),"[nW cm-2
str-1]")
#print("Area under 15m depth graph:",Integral(HPS_Ray*viirs_scaling_HPS,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(HPS_Ray2*viirs_scaling_HPS,new_wave),"[nW cm-2 str-1]")
#print("Area under surface graph:",Integral(HPS_RI*SQM_scaling_HPS,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth graph:",Integral(HPS_Ray*SQM_scaling_HPS,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(HPS_Ray2*SQM_scaling_HPS,new_wave),"[nW cm-2 str-1

#print("Area under surface graph:",Integral(INC_RI*viirs_scaling_INC,new_wave),"[nW cm-2
str-1]")
#print("Area under 15m depth graph:",Integral(INC_Ray*viirs_scaling_INC,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth grahp:",Integral(INC_Ray2*viirs_scaling_INC,new_wave),"[nW
cm-2 str-1]")
#print("Area under surface graph:",Integral(INC_RI*SQM_scaling_INC,new_wave),"[nW cm-2
str-1]")
#print("Area under 15m depth graph:",Integral(INC_Ray*SQM_scaling_INC,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(INC_Ray2*SQM_scaling_INC,new_wave),"[nW cm-2 str-1]")

#print("Area under surface graph:",Integral(MH_RI*viirs_scaling_MH,new_wave),"[nW cm-2
str-1]")
```

```
#print("Area under 15m depth graph:",Integral(MH_Ray*viirs_scaling_MH,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth grahp:",Integral(MH_Ray2*viirs_scaling_MH,new_wave),"[nW
cm-2 str-1]")
#print("Area under surface graph:",Integral(MH_RI*SQM_scaling_MH,new_wave),"[nW cm-2
str-1]")
#print("Area under 15m depth graph:",Integral(MH_Ray*SQM_scaling_MH,new_wave),"[nW
cm-2 str-1]")
#print("Area under 30m depth
graph:",Integral(MH_Ray2*SQM_scaling_MH,new_wave),"[nW cm-2 str-1]")

#print("Area under surface graph:",Integral(HALO_RI*viirs_scaling_HALO,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth
graph:",Integral(HALO_Ray*viirs_scaling_HALO,new_wave),"[nW cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(HALO_Ray2*viirs_scaling_HALO,new_wave),"[nW cm-2 str-1]")
#print("Area under surface graph:",Integral(HALO_RI*SQM_scaling_HALO,new_wave),"[nW
cm-2 str-1]")
#print("Area under 15m depth
graph:",Integral(HALO_Ray*SQM_scaling_HALO,new_wave),"[nW cm-2 str-1]")
#print("Area under 30m depth
grahp:",Integral(HALO_Ray2*SQM_scaling_HALO,new_wave),"[nW cm-2 str-1]")
```

Migratory bird report

Species	Observation	Fraction	Independ X	Increase of X	Percentile increase
Eurasian Spoonl	126	1.26	1	2.26	
Barnacle Goose	62.5	0.63	1	1.625	
Common Teal	60	0.60	1	1.6	
Northern Pintail	58.75	0.59	1	1.5875	
Northern Shovel	57.5	0.58	1	1.575	
Ruff	50.15	0.50	1	1.5015	
Ruddy Turnstone	35	0.35	1	1.35	
Eurasian Wigeor	32.5	0.33	1	1.325	
Sanderling	27.5	0.28	1	1.275	
Common Ringec	26.25	0.26	1	1.2625	
Eurasian Golder	23.75	0.24	1	1.2375	
Black-headed Gı	17.5	0.18	1	1.175	
Kentish Plover	16.25	0.16	1	1.1625	
Great Cormoran	15	0.15	1	1.15	
Whimbrel	11.25	0.11	1	1.1125	
Grey Plover	10	0.10	1	1.1	
Brent Goose	8.75	0.09	1	1.0875	
Northern Lapwin	7.5	0.08	1	1.075	
Common Redsh	6.25	0.06	1	1.0625	
European Herrin	5	0.05	1	1.05	
Red knot	2.5	0.03	1	1.025	
Bar-tailed Godwi	1.25	0.01	1	1.0125	
Eurasian Curlew	-5	-0.05	1	0.95	
Dunlin	-6.25	-0.06	1	0.9375	
Common Gull	-7.5	-0.08	1	0.925	
Common Green	-12.5	-0.13	1	0.875	
Common Eider	-13.75	-0.14	1	0.8625	
Common Sheldu	-16.25	-0.16	1	0.8375	
Eurasian Oyster	-16.25	-0.16	1	0.8375	
Great Black-bacl	-16.25	-0.16	1	0.8375	
Mallard	-18.75	-0.19	1	0.8125	
Curlew Sandpipe	-21.25	-0.21	1	0.7875	
Spotted Redsha	-22.5	-0.23	1	0.775	
Pied Avocet	-32.5	-0.33	1	0.675	
SUM			34	38.724	113.89%

Migratory bird population increase in the Wadden Sea observed from [Kleefstra 2022, et al]