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OVERVIEW

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How dark is a river? Artificial light at night in aquatic systems and the need for comprehensive night-time light measurements

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Abstract
Freshwater ecosystems are hotspots of biodiversity. They are of major importance for humans because they provide vital ecosystem services. However, as humans tend to settle near freshwaters and coastal areas, these ecosystems are also over-proportionally affected by anthropogenic stressors. Artificial light at night can occur as a form of environmental pollution, light pollution. Light pollution affects large areas on a worldwide scale, is growing exponentially in radiance and extent and can have diverse negative effects on flora, fauna and on human health. While the majority of ecological studies on artificial light at night covered terrestrial systems, the studies on aquatic light pollution have unraveled impact on aquatic organisms, ecosystem functions as well as land-water-interactions. Although monitoring of light pollution is routinely performed from space and supported by ground-based measurements, the extent and the amount of artificial light at night affecting water bodies is still largely unknown. This information, however, is essential for the design of future laboratory and field experiments, to guide light planners and to give recommendations for light pollution regulations. We analyze this knowledge gap by reviewing night-time light measurement techniques and discuss their current obstacles in the context of water bodies. We also provide an overview of light pollution studies in the aquatic context. Finally, we give recommendations on how comprehensive night-time light measurements in aquatic systems, specifically in freshwater systems, should be designed in the future.

This article is categorized under:
Water and Life > Stresses and Pressures on Ecosystems
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Water and Life > Methods

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ALAN, artificial light at night, light measurement, light pollution

1 | INTRODUCTION

Freshwater ecosystems such as streams, rivers, channels, lakes and ponds occupy less than 1% of the Earth's surface but are biodiversity hotspots comprising 10% of all known species, and about 30% of vertebrate species (Balian, Segers, Lévèque, &

Martens, 2008; Dudgeon et al., 2006). Freshwaters provide important ecosystem services such as food and drinking water supply and serve recreational purpose. Thus, humans tend to settle close to water bodies. More than 50% of the world's population live within a distance of 3 km and only 10% more than 10 km away from a water body (Kummu, De Moel, Ward, & Varis, 2011). As a result, freshwaters and marine coastal areas are most heavily impacted by anthropogenic stressors (Dudgeon et al., 2006; Venohr et al., 2018). Increasing human activities pose challenges to these fragile ecosystems such as habitat degradation, multilevel pollution, flow regulation, overfishing, and the introduction of alien species (Strayer & Dudgeon, 2010). Artificial light at night (ALAN) can occur as an environmental stressor: Light pollution. Because ALAN is linked closely to human activity (Elvidge et al., 1997), it is assumed to affect freshwater systems and coastal areas disproportionally (Zhao, Li, Li, Zhao, & Wu, 2018). The effects of ALAN on aquatic organisms and communities have been researched in several laboratory (Brüning, Hölker, Franke, Kleiner, & Kloas, 2016; Brüning, Hölker, Franke, Preuer, & Kloas, 2015; Hölker et al., 2015; Kurvers et al., 2018; Perkin, Hölker, Heller, & Berghahn, 2014c; Poulin et al., 2013; Szekeres et al., 2017) and field studies (Becker, Whitfield, Cowley, Järnegren, & Næsje, 2013; Bolton et al., 2017; Brüning, Kloas, Preuer, & Hölker, 2018a; Cullen & McCarthy, 2000; Davies, Duffy, Bennie, & Gaston, 2016; Grubisic et al., 2017; Grubisic, van Grunsven, Manfrin, Monaghan, & Hölker, 2018; Hölker et al., 2015; Ludvigsen et al., 2018; Manfrin et al., 2017, 2018; Meyer & Sullivan, 2013; Moore, Pierce, Walsh, Kvalvik, & Lim, 2001; Perkin, Hölker, & Tockner, 2014b; Perkin, Hölker, Tockner, & Richardson, 2014a; Riley, Bendall, Ives, Edmonds, & Maxwell, 2012; Riley, Davison, Maxwell, & Bendall, 2013; Szaz et al., 2015; Tabor, Brown, & Luiting, 2004; Underwood, Davies, & Queirós, 2017). However, we found a knowledge gap regarding the status quo of light pollution in and along aquatic systems. There is a clear lack of measured in-situ light at night data and several obstacles for remote sensing approaches of water bodies, in particular for freshwater systems, exist. However, the information of how much ALAN is present in aquatic ecosystems is important for several stakeholders. For example, light planners, lighting designers, politicians and conservation agencies need guidance when new lighting technology is to be installed near water bodies. Researchers need to know realistic ALAN levels for the experimental design of laboratory and field studies on light pollution. Furthermore such data are essential for the development of regulations and laws (especially for protected areas), which do not exist for water bodies so far.

In this paper, we will briefly summarize the background of natural and ALAN and the state of the art of light pollution measurements. We then review recent scientific findings regarding ALAN and aquatic systems as well as published data of light pollution measurements in and along aquatic systems. Finally, we discuss future challenges, the possibilities and obstacles of different measurement approaches and outline a possible route to fill existing knowledge gaps.

2 | NATURAL AND ALAN AND LIGHT POLLUTION

Light is one of the most important abiotic factors on Earth. The illuminance from natural light sources (the sun, moon, stars, and atmospheric effects such as airglow) covers a large dynamic range of about nine orders of magnitude. During the day it ranges from a maximum of about 100,000 lx to about 800 lx at sunset. At night it reaches a maximum of about 0.3 lx at a full-moon night, decreases to about 0.001 lx at a moonless clear night (Hänel et al., 2018) and even further for cloudy conditions (Jechow & Hölker, 2019; Jechow, Hölker, & Kyba, 2019a). The light cycle between night and day, the lunar cycle, weather or seasons serve as external cues (zeitgeber) for cyclic biological processes such as reproduction and foraging (Kronfeld-Schor & Dayan, 2003; Robert, Lesku, Partecke, & Chambers, 2015). In aquatic systems, the water is an additional "optical filter" that alters the wavelength (color), direction, and polarization of the incident light (Mobley, 1994).

Humans are strictly diurnal, but the invention of ALAN has allowed humans to extend their activity and productivity deeply into the night, resulting almost in a 24-hr society. Nowadays, ALAN has become a sign of wealth, security, and prosperity and the term "light poverty" is used to describe the lack of electricity in less-developed regions of the world (Barki, Barki, & Habbu, 2008). ALAN as a form of environmental pollution, light pollution, was first recognized by astronomers (Riegel, 1973) but has also implications for flora and fauna (Schroer & Hölker, 2017) and human health (Cho et al., 2015). Although some studies regarding ALAN and the environment date back to early observations on trees (Matzke, 1936) and insects (Eisenbeis, 2006), it was more recently that the term ecological light pollution was coined (Longcore & Rich, 2004). The ecological consequences cover a wide range of species, communities, and ecosystems effects (Gaston, Visser, & Hölker, 2015) and light pollution is also recognized as a potential threat to biodiversity (Hölker, Wolter, Perkin, & Tockner, 2010b). Ecological light pollution can basically be defined as the presence of artificial light with an intensity (respectively irradiance or illuminance), a spectral composition or polarization at times that do not correspond to natural nocturnal light and which has negative ecological effects (Gaston et al., 2015).

FIGURE 1 Wide field image of the skyglow of two distant towns at the coast of the Baltic Sea photographed southward from Pape Nature Reserve in Lavia 2018

Light pollution is commonly categorized into direct and indirect effects. Direct light pollution originates from light emission that is directly incident on a land or water surface. In urban areas, such direct ALAN can reach light levels up to 1,000 times brighter than a clear full-moon night (Hänel et al., 2018). Indirect light pollution originates from light that is diverted by reflection at surfaces or scattering within the atmosphere, then occurring as skyglow (Rosebrugh, 1935). Skyglow (Figure 1) is visible over large distances and can result in night sky brightness levels hundreds of times higher than natural (Kyba et al., 2015b) and illuminance levels higher than full moon (Jechow & Hölker, 2019). Skyglow changes with atmospheric and weather conditions (Jechow et al., 2017b, 2018; Kyba, Tong, et al., 2015b).

According to a skyglow model based on satellite data (Falchi et al., 2016), more than 80% of the world population and more than 99% of the population in the United States and Europe live under light-polluted skies. The Milky Way is hidden from more than one-third of humanity (Falchi et al., 2016). Furthermore, ALAN is increasing exponentially both in lit area and in brightness worldwide at rates of more than 2% per annum on global average (Hölker et al., 2010a; Kyba et al., 2017) and peaks at rates of more than 40% in the developing world (Kyba et al., 2017 supplement). The so-called lighting revolution (Pust, Schmidt, & Schnick, 2015), the switch to energy-efficient LED lighting technology, presumably suffers from a rebound effect that results in higher usage rather than in net savings (Kyba et al., 2017).

3 | STATE OF THE ART IN LIGHT POLLUTION MEASUREMENTS

3.1 | A short overview of relevant radiometry and light propagation basics

Light measurements may appear to be straightforward, but different physical quantities and different units used across different disciplines often cause confusion. In this subsection, we very briefly review the necessary background on radiometry for light measurements in waters and at night. As it is impossible to be comprehensive here, we recommend to newcomers Johnsen (2012), which provides an accessible but physically correct account.

Consider first the geometry. The radiance L is the light incident from a specific solid angle, while the irradiance E is the total flux of light incident on a surface. See Figure 2a for a schematic drawing of measurement of the radiance of the sky L_{sky} (specifically L_{zenith} at zenith) and the surface irradiance at the Earth surface. Irradiance in aquatic systems is commonly further differentiated into scalar E_{scalar} (sometimes E_0) (Smith & Wilson, 1972) and vector or plane irradiance E_{plane} (Figure 2b) with vector irradiance being the light incident on a plane surface (most commonly, the horizontal plane $E_{\mathrm{horizontal}}$ is used) and scalar irradiance being the light incident on a sphere. The direction of radiance is important and is commonly distinguished in upwelling (e.g., seen by satellite) and downwelling (e.g., measured by ground-based sensor).

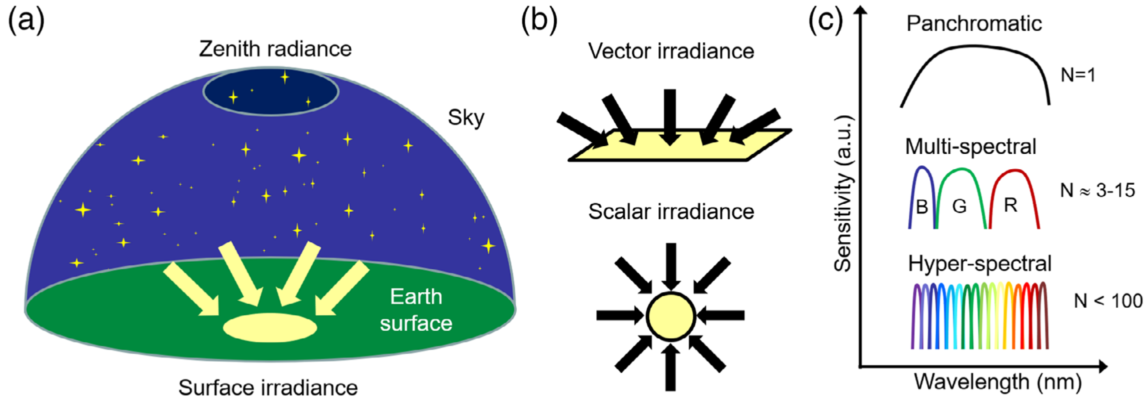

FIGURE 2 Schematic drawing of different radiometric parameters. (a) Geometry of sky and zenith radiance and surface irradiance measurements, (b) vector and scalar irradiance, and (c) different spectral bands

In the spectral domain, radiance and irradiance are defined according to spectral sensitivity or "band". Panchromatic sensors (Figure 2c upper graph) measure the radiance in a single band, sometimes due to the sensors own sensitivity (e.g., silicon) or by adding filters to target a specific application. The luminance L_v, for example, is the radiance referenced to the (daytime) sensitivity of the human eye and illuminance E_v would be the irradiance equivalent. Another commonly used quantity in biology is photosynthetically active radiation (PAR) L_{PAR} that weights the incident number of photons equally (not energy) between 400 and 700 nm. To achieve spectral resolution, multiple bands have to be measured. Nowadays, the terms multispectral and hyperspectral are commonly used to distinguish sensors, although this is not strictly defined. Multispectral sensors have several discrete bands, typically 3 to about 20, realized with optical filters. For example, a digital consumer camera with RGB sensor qualifies as multispectral sensor measuring $L_{R,\ G,\ B}$ (Figure 2c middle graph). A hyperspectral sensor has many (typically narrow) discrete bands and spans over a continuum of wavelengths measuring L_λ (Figure 2c lower graph). There is no strict lower boundary of number of bands but usually this is several tens of bands or more than 100. Conversion between bands (e.g., from luminance to PAR radiance) is not straightforward and only possible if the spectrum of the light and the sensor sensitivity is known. However, an approximation is sometimes possible for common situations like (clear sky) daylight.

In a medium like air or water, the main processes relevant for the topic of this paper are absorption, emission and scattering. Simplified, absorption is the annihilation of a photon, emission the creation of a photon and scattering is the change of a photon's original propagation direction in a bulk medium. At boundaries, like for example the water–air interface, the light changes direction by refraction (following Snell's law) or reflection (following the Fresnel equations). As the latter depends on the polarization of light, light propagating from air into water or light that is reflected from water has usually a higher degree of polarization than light that did not experience such a boundary. The interplay between spectrum of incident light, absorption and scattering (both depending on the water itself but also its constituents) will define the spectrum of upwelling, water leaving radiance $L_{\lambda,\ up,\ water}$ (the "water color") that can then be used for near-surface or remote sensing of water constituents, for example to measure algal blooms from space (Pahlevan, Sarkar, Franz, Balasubramanian, & He, 2017). For an introductory overview we recommend Mobley (1994).

3.2 | Remote sensing of ALAN

The Earth is routinely monitored from space by satellite technology and global images of the Earth at night are well known from television (e.g., weather forecasts). However, the fact that ALAN can be seen from space by naked eye is less well known but was already reported by astronaut John Glenn in 1962 during the first crewed U.S. American orbital flight where he "saw a very bright light and what appeared to be the outline of a city" which was Perth in Australia (Swenson Jr, Grimwood, & Alexander, 1966).

The most common night-time sensors measure the upwelling radiance in a single panchromatic band. The first widely applied night-time satellite data set is based on the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) sensor, which has collected digital data since 1992. The DMSP/OLS global time series of night lights with 3-km resolution enabled the study of urbanization, socioeconomic changes, expansion of road networks and the result of armed conflicts (Bennett & Smith, 2017), but suffers from calibration issues. The Day and Night Band (DNB) sensor of the

Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suomi National Polar-orbiting Partnership (Suomi NPP) satellite is tailored for night-time lights (Miller et al., 2012) and significantly improvement over DMSP/OLS. VIIRS/DNB has a higher spatial resolution of 750 m, is radiometrically calibrated, sensitive to lower light levels and does not saturate in urban areas (Elvidge, Baugh, Zhizhin, Hsu, & Ghosh, 2017). Both DMSP/OLS and VIIRS/DNB represent the state of the art in global night-time light data that is freely available. Both sensors have been the basis for global skyglow models (Falchi et al., 2016). These global skyglow models assume a certain spatial distribution of a light source, also called city emission function (Lamphar, 2018) and normally default scattering parameters. However, the limited spatial resolution and the limited spectral sensitivity of both panchromatic sensors are nonideal for monitoring light pollution in aquatic systems, particularly for smaller freshwater bodies.

Promising novel spaceborne technologies are multispectral (red, green and blue, RGB) photographs made by astronauts from the international space station (ISS) (Kyba et al., 2015a), as shown in Figure 3, or small satellites of the CubeSat series such as the (panchromatic) Luojia 1-01 (Jiang et al., 2018). However, while the former data are free but require post calibration and geo-referencing the latter data have low revisit time and or very low data coverage and are usually operated commercially. Nevertheless, a promising platform is the commercial Chinese JL1-3B satellite, offering multispectral (RGB) night-time light data at very high spatial resolution of 0.92 m (Zheng et al., 2018). Fine spatial resolution can be achieved with airborne sensors as shown with a panchromatic camera at 1 m spatial resolution in Berlin (Kuechly et al., 2012) and even with hyperspectral cameras in Las Vegas (Kruse & Elvidge, 2011). However, such cost intensive aerial campaigns cannot provide continuous global monitoring of urban areas.

3.3 | Ground-based measurements of ALAN

ALAN incident at the water surface or propagating under water can be measured with several different instruments. A classic instrument to determine visible ALAN is a luxmeter, measuring illuminance, that is, all light incident at a surface, which usually is a plane or a sphere (see Figure 2b) in a single spectral band matching the human photopic vision. The most common way would be to determine horizontal illuminance with a cosine corrector. However, the drawback of a luxmeter is the lack of spectral information, which is very important for ecological questions. This can be overcome by measuring the spectral irradiance with a hyperspectral sensor (Figure 2c) as demonstrated at night-time with fiber-coupled commercial spectrometers (Ludvigsen et al., 2018; Secondi et al., 2017; Spitschan, Aguirre, Brainard, & Sweeney, 2016). Still this procedure lacks information about the directionality, which can be either obtained by scanning systems (i.e., rotational mounts) or wide-angle imaging devices. Directionality is important for ALAN in aquatic systems, because of the nonisotropic reflection, polarization level and different path lengths for light traveling to a specific point inside the water volume (Mobley, 1994).

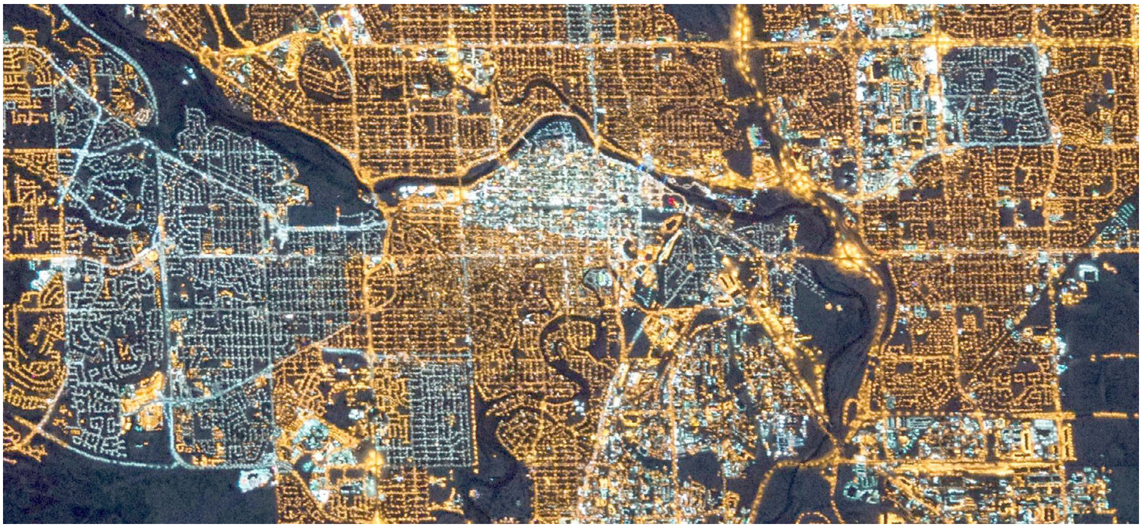

FIGURE 3 Night-time image of Calgary, CA, taken on November 28, 2015 from the international space station (ISS), showing the city lights and part of the Bow River in the downtown area. Original image by NASA, photo ID ISS045-E-155029. Please note that water bodies appear as the darkest regions in the image, for example the Bow River meandering as dark band across the image being intersected by linear lit structures (bridges, see Fig. 8)

Unfortunately, most optical devices designed for outdoor and underwater use are tailored for daytime applications and lack sensitivity for low night-time radiance or illumination levels. Several techniques for ground-based observations of the night sky brightness have been established within astronomy (see review by Hänel et al., 2018). The most common technique is to perform point measurements of the zenith radiance (see Figure 2a) with a panchromatic radiometer like the Sky Quality Meter (SQM, Unihedron, Canada). A more advanced but less widespread technique is to acquire multispectral (RGB) all-sky images with a digital camera and a 180° fisheye lens. The camera measures the spatially resolved radiance over the whole hemisphere in three spectral bands in one image by a single measurement. The method is therefore quick, can provide many measurements per timeframe (Jechow, 2019; Jechow et al., 2018), is easily applicable during field work (Jechow et al., 2017a; Jechow, Kolláth, Ribas, et al., 2017b; Jechow, Kyba, & Hölker, 2019b), and can help to extract the city emission function crucial for skyglow models (Kocifaj, Solano-Lamphar, & Videen, 2019). Figure 4 shows a false color luminance map acquired with this method at Pape Nature Reserve at the Baltic Sea (same location as Figure 1). At this site, the impact of light pollution is relatively low with near natural zenith brightness and Milky Way visible directly above. However, there is also some significant skyglow near the horizon (compare with Figure 1).

A recent modification of the night-time all-sky architecture includes taking multiple images to get information on the light field from all directions (Jechow, Kyba, & Hölker, 2019b), which was applied in oceanography as early as 1970 with film cameras back to back for daytime operation up to 100 m depth (Smith, Austin, & Tyler, 1970). To get the full spectral radiance and directionality, a hyperspectral imaging system with a wide-angle optics, ideally dual fisheye lens geometry (Smith et al., 1970), would be required. At the moment no such system exists out of the box, but promising ground-based measurements in an urban context have been performed recently at night (Alamús et al., 2017) and hyperspectral imaging was performed with active light sources under water (Dumke et al., 2018).

4 | LIGHT POLLUTION AND AQUATIC SYSTEMS

4.1 | A brief overview of ecological effects

ALAN has several negative consequences on aquatic systems and their surroundings as demonstrated on almost all trophic levels and for a wide variety of consequences. Effects at small scales include changes in community composition and phytophysiology for microorganisms (Hölker et al., 2015), cyanobacteria (Poulin et al., 2013) and periphyton communities (Grubisic et al., 2017, 2018). Zooplankton is affected by very low levels of ALAN. It was shown that the amplitude of diel vertical migration of zooplankton is influenced even by skyglow (Moore et al., 2001). Ludvigsen et al. (2018) observed that

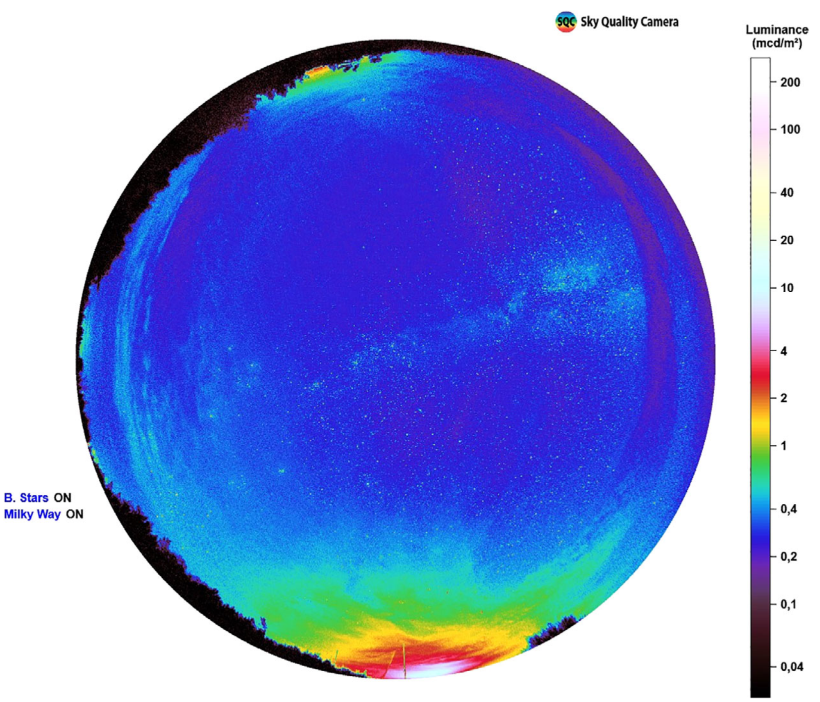

FIGURE 4 All-sky luminance map obtained with a DSLR camera and a fisheye lens at the same position as Figure 1

the lights from ships can induce also horizontal movement rendering it impossible to determine the diel vertical migration of arctic zooplankton in an arctic fjord during polar night by ship-based net measurements.

It is well known that many nocturnal insects are attracted by lamps and can become disoriented, exhausted, and finally an easy prey, which has been termed the "vacuum cleaner effect" (Eisenbeis, 2006). Aquatic insects seem to be particularly affected by ALAN as shown with streetlamps in field studies (Manfrin et al., 2017; Perkin, Hölker, & Tockner, 2014b) and by studying light polarization at bridges (Szaz et al., 2015).

Hormone-controlled physiological processes can be influenced by ALAN, like the release of melatonin in perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) (Brüning et al., 2015), which is probably important for sexual maturation as demonstrated for perch and roach in both, field and laboratory experiments (Brüning et al., 2015, 2016, 2018a,b).

Over larger spatial scales, ALAN can induce food web distortions and influence the transfer of organic matter (here insects) between aquatic and terrestrial ecosystems (Manfrin et al., 2017; Meyer & Sullivan, 2013; Perkin et al., 2011). Predator–prey relationships can be influenced by ALAN as shown for pacific salmon (*Oncorhynchus clarki*) (Mazur & Beauchamp, 2006), bullheads (*Cottus* sp.) and juvenile red salmon (*Oncorhynchus nerka*) (Tabor et al., 2004), yellowfin bream (*Acanthopagrus australis*), leatherjackets (Monocanthidae) (Bolton et al., 2017) as well as for seals (*Phoca vitulina*) (Yurk & Trites, 2000) and riparian consumers such as spiders and harvestman (Manfrin et al., 2018; Sullivan, Hossler, & Meyer, 2019).

The presence of ALAN has also shown to alter daytime behavior of certain species. For example, nocturnal riparian spiders shift foraging activities into the day (Manfrin et al., 2017). Guppies (*Poecilia reticulata*) have shown higher risk taking during the day when being exposed to ALAN in contrast to the control group not exposed to ALAN (Kurvers et al., 2018).

ALAN can be a major disruption, especially for linear water bodies like rivers and canals. There, the direct influence of lighting at banks, harbors, bridges, or roads running parallel to the watercourse can have a major impact on aquatic and riparian ecosystems. Analyses of nocturnal aerial photographs of Berlin have shown that rivers and canals are approximately six times brighter than lakes due to their large ratio of shore length to water surface (Kuechly et al., 2012). Streetlights and lit structures can impose a dispersal barrier for flying insects important for aquatic systems as demonstrated with moths in field experiments (Degen et al., 2016). Furthermore, illuminated riverside roads form continuous "interaction edges," where fluxes of organisms and nutrients between aquatic and terrestrial ecosystems may be altered by ALAN (Manfrin et al., 2017, Meyer & Sullivan, 2013). This can lead, for example, to the fragmentation of habitats solely because of lighting effects.

Illuminated overpass and crossing structures such as bridges and weirs impose barriers for migratory fish, bats and macroinvertebrates species. Some salmonid fish and eels occasionally interrupt their migration at such structures (Cullen & McCarthy, 2000; Lowe, 1952; Nightingale, Longcore, & Simenstad, 2006). In addition, Riley et al. (2012, 2013) showed that low brightness street lighting results in delayed spread of Atlantic salmon fry (*Salmo salar*). For many bat species, lighting of waterways and crossing structures may have serious negative consequences as they are important flyways and feeding sites (Kuijper et al., 2008). Female mayflies, performing their upstream compensatory flight, were attracted upward toward bridge lamp light (Szaz et al., 2015). ALAN, therefore, can increase the so-called space resistance of a landscape. As a result, the migration can be more time and energy consuming, which can endanger the natural synchronized reproduction, especially for long-distance migratory species such as salmon or eels (Vøllestad et al., 1986).

4.2 | Light pollution measurements in aquatic systems

Despite the many studies of ALAN in general and the variety of studies of ALAN in an aquatic context, it is very surprising that there are only very few quantitative datasets published on how aquatic systems are affected by ALAN.

4.2.1 | Remotely sensed data

Several examples have used remotely sensed data in the context of ALAN and aquatic systems. In a seminal study, Fett (1975) reported fishing boats using lights already in the 1970s and lit ships and light fishing activities have been reported by night-time data ever since (Waluda, Yamashiro, Elvidge, Hobson, & Rodhouse, 2004). Aubrecht et al. (2008) used DMSP satellite data to create a global inventory of three reef stressors: development, gas flaring and heavily lit fishing boats using an artificial night-time lights proximity index. The results indicated that coral reefs in Puerto Rico and regions in the Red Sea and in the Persian Gulf are extremely endangered by cities and towns. Davies, Duffy, Bennie, and Gaston (2014) were reviewing the extent of marine light pollution and used DMSP/OLS data from 2010 to estimate that 22.2% of the world's coastlines (excluding Antarctica) and more than half of Europe's coastline were exposed to ALAN. In a follow-up on that, Davies et al. (2016) used DMSP/OLS data to investigate the extent to which marine protected areas are affected by ALAN and how it changes over time. They found that more than one third of the protected areas were experiencing ALAN and that the amount of ALAN was increasing in these areas. They also proposed to establish "Marine Dark Sky Parks" to also protect such fragile ecosystems from light pollution. Recently, Gillespie et al. (2017) used DMSP/OLS time series to investigate the Mediterranean Coast Network of Southern California and found no big changes in night-time lights over time. We want to point out again that time series with DMSP/OLS have to be treated with caution as they are not well calibrated (Kyba et al., 2017).

With the advent of the advanced VIIRS/DNB data that provide calibrated information, more studies are emerging. Zhao et al. (2018) analyzed global VIIRS/DNB data in the context of oceans and showed that the distribution of light at night is clustered, and mainly concentrated in coastal and offshore waters, with about 70% of the total light found in 0.3% of the global marine waters. Elvidge, Zhizhin, Baugh, and Hsu (2015) could develop an algorithm to identify light fishing and Geronimo et al. (2018) observed light fishing activities with VIIRS data in high spatial resolution. Hu, Hu, and Huang (2018) analyzed VIIRS/DNB data and found a significant negative correlation between light pollution and sea turtle nesting, highest for green turtles, lowest for leatherbacks and intermediate for loggerheads.

To our knowledge, freshwater systems have not been studied with satellite data, which is not surprising as most freshwater bodies have a small extent and rivers and small ponds cannot be resolved at 750 m spatial resolution provided by VIIRS/DNB global products. The only remotely sensed dataset investigating ALAN of freshwater bodies was an airborne study by Kuechly et al. (2012). They showed that flowing waters like rivers and canals (1.5% of the area) in Berlin reach a brightness factor of 0.26 and standing waters (3.5% of the area) like lakes only a brightness factor of 0.045. This means rivers were almost six times brighter than lakes in this study. For comparison: they defined the brightness factor of 1 as the average of all their data. In this case, streets made up 13.6% of the area and had a brightness factor of 2.3.

4.2.2 | In situ ALAN measurements

While airborne data are extremely challenging regarding logistics (planning, weather, permits), costs, georeferencing and data analysis, ground-based measurements at the water surface can be easily obtained with luxmeters or spectrometers. However, to our knowledge very few published datasets exist. Some of these data are hidden in research papers that focus rather on effects than quantifying night-time light levels and the extent of ALAN.

The most widespread method to measure ALAN in freshwaters uses simple handheld luxmeters above the water surface. Mazur and Beauchamp (2006) measured values between 1 and 20 lx at Lake Washington in Seattle; Meyer and Sullivan (2013) between 0.1 and 12 lx at several urban and peri-urban rivers in Columbus and Riley et al. (2012) between 2 and 14 lx from streetlights at a tributary of the river Itchen in southern England. Perkin, Hölker, Heller, and Berghahn (2014c) did a survey of rivers in Berlin where sites were picked from aerial data (Kuechly et al., 2012). They measured light levels at the River Spree, Berlin, Germany, 0.5 m below the surface with a sensitive (<0.002 lx) underwater luxmeter (ILT1700) measuring between 0.008 and 1.4 lx. The same lightmeter was used in a field experiment with standard streetlamps, where light levels between 13 and 17 lx were measured at the water surface and between 6 and 9 lx at the sediment surface (0.5 m depth) of a ditch in Westhavelland, Brandenburg, Germany (Hölker et al., 2015).

Luxmeters (and similar panchromatic devices like PAR sensors) lack spectral information, which is however important for ecological studies. Only very few spectrally resolved measurements at night-time for aquatic systems exist. Secondi et al. (2017) surveyed ALAN in 26 ponds and 2 river sites in Angers Loire Métropole. They measured spectral downwelling irradiance in a wavelength range of 300–700 nm by using a fiber-coupled hyperspectral sensor equipped with a cosine corrector. They further estimated underwater light intensities by obtaining in situ water samples. Their procedure was to determine the wavelength-specific attenuation coefficients of the water samples in the laboratory. Then the expected irradiance was calculated for two depths 0.5 and 1 m, relevant for shallow ponds. The aim of their study was to evaluate the impact of cloud coverage on the amount of ALAN present at their study sites.

Ludvigsen et al. (2018) performed transects in an arctic fjord with an autonomous surface vehicle to investigate diel vertical migration of zooplankton during the polar night. They used a fiber-coupled hyperspectral sensor and a reflectance standard plate to measure spectral downwelling irradiance and a radiative transfer model to calculate the spectral irradiance at the depths relevant for their experiment.

Tamir, Lerner, Haspel, Dubinsky, and Iluz (2017) measured underwater spectra at 19 locations at different depths in the coastal waters of the Gulf of Eilat, Israel with a profiling multispectral radiometer with 12 spectral channels between 300 and 900 nm and mapped the extend of ALAN for these waters. They showed that wavelengths at 589 and 443 nm can still be detected in depths greater than 10 m at a great distance from the shore. They further determined that the irradiance at a wavelength of 589 nm during a moonless night near the shore can exceed the values measured during full moon at a point away from the shore.

Several ALAN measurements at aquatic systems were performed with tools from the astronomical community. Jechow, Hölker, Kolláth, Gessner, and Kyba (2016) measured the night sky brightness on a freshwater lake, Lake Stechlin, near Berlin Germany from a swimming platform. They used a commercial DSLR camera with a fisheye lens to acquire all-sky and vertical plane hemispherical images and a small single-channel SQM photometer for long-term measurements. Jechow, Kolláth, Lerner, et al. (2017a) later showed that the DSLR method can also be used from a moving boat, taking measurements in the Gulf of Eilat near some measurement spots of Tamir et al. (2017).

Ges, Bará, García-Gil, Zamorano, and Masana (2018) compared the predictions of the skyglow model by Falchi et al. (2016) to SQM observations made during a transect with a boat from Barcelona, Spain, out to sea. They found very good agreement with the model at atmospheric conditions similar to those used in the model, but disagreement of up to 50% on a night with better atmospheric conditions. In particular, they found that on a night with low aerosol load, the sky was darker than predicted near Barcelona, while far out to sea the sky was brighter than predicted.

The only attempt to use an SQM photometer underwater was just recently performed by Bará et al. (2018). They investigated light pollution in shallow coastal waters in the context of aquaculture farming in the Galician Atlantic shoreline in Spain.

Finally, citizen science has becoming an indispensable tool for both data collection and knowledge dissemination, especially for collecting data on larger scales, such as at landscape level. For example, several citizen science projects assist in collecting data about the brightness of nightscapes from the ground (Kyba, Tong, et al., 2015b; Schroer et al., 2018). However, to our knowledge there is only one citizen science study so far that has been developed to describe local nocturnal artificial light conditions of aquatic systems, in this case by using questionnaires (Schroer et al., 2016).

5 | DISCUSSION AND FUTURE DIRECTIONS

The literature review shows that measurements of night-time light levels in the context of aquatic light pollution are scarce and no common strategy to acquire such data exist, yet. To fully assess the impacts of ALAN on water bodies, however, it is necessary to know how much ALAN is present at specific locations, ideally with spectrally resolved three-dimensional maps of ALAN levels as produced by Tamir et al. (2017). Knowledge of ALAN levels present at a specific water body is also essential for the design of future ALAN laboratory and field studies on species and ecosystem level. Laboratory studies using current ALAN scenarios or extrapolating future ALAN scenarios become more meaningful with real-world data. Furthermore, it is necessary to support recommendations for light pollution regulation laws with data, especially for protected areas and endangered species like eels. Finally, such data and measurements can help light planners and lighting designers to install sustainable and ecosystem friendly lighting technology along and near water bodies with minimized light pollution. In this section we will discuss the possibilities and specific challenges of night-time light measurements in the aquatic context and outline a possible strategy to acquire such data.

5.1 | Possibilities and obstacles for night-time remote sensing of water bodies

One of the biggest obstacles for studies of night-time lights in the aquatic context from space is the spatial resolution, particularly for small inland waters (rivers, streams, small lakes and ponds etc.). From the abovementioned work using satellite remote sensing, only four focused on measurements (Davies et al., 2014, 2016; Gillespie et al., 2017; Zhao et al., 2018) and only Zhao et al. (2018) used the calibrated VIIRS/DNB sensor with the higher spatial resolution of 750 m. The only high-resolution dataset ever produced that deals with water bodies (we are aware of) is the aerial survey of Berlin performed in 2010 with 1 m spatial resolution (Kuechly et al., 2012). They analyzed different land use categories including standing and flowing waters and tested at what spatial resolution a significant loss of information due to spatial binning occurs. They judged that images from space should have at least 10 m spatial resolution to fully distinguish dark and lit areas in land use classes. We are optimistic that more work on aquatic systems using VIIRS/DNB will follow, mainly for coastal regions and large inland waters. Promising for future studies on smaller scales are new CubeSat satellites like the Luojia-1-01 or JL1-3B and astronaut photographs from the ISS (Figure 3). However, even at very fine spatial resolution, several principle challenges for remote sensing of night-time lights and water bodies remain. These include, for example, the low reflectance of water bodies, specular reflections and the unknown ratio between upwelling and downwelling light emitted by lamps or from the ground.

A general problem of optical remote sensing is cloud cover that prevents detection of light emitted from the Earth surface both night and day. However, clouds can dramatically amplify the effects of skyglow increasing the downwelling part of ALAN (Jechow & Hölker, 2019; Jechow, Hölker, & Kyba, 2019a; Jechow, Kolláth, Ribas, et al., 2017b; Secondi et al., 2017). The extent of this effect can only be detected by ground-based light measurements.

In most cases, the angular emission distributions of lamps or lighting scenarios (including ground and façade reflections etc.) are not known and airborne and spaceborne sensors can only detect upwelling radiation within a small angle around nadir. This imposes challenges not only in estimating the fraction of light that is downwelling but also the angle of incidence at the water. However, for ALAN in aquatic systems the downwelling radiation incident from multiple angles is the important factor to know, as this is important for the further propagation at the water–air interface (reflection, refraction, and polarization).

Figure 5 schematically shows three possible emission scenarios of lamps (a) a lamp radiating in all directions with direct uplight and a fraction of uplight that is reflected on the ground from a larger area, (b) a fully cut-off lamp with no direct uplight but a large horizontal component that increases scattering or reflections resulting in uplight, and (c) a modern lamp with no direct uplight and optics guiding the light were it is needed resulting in a small area that is creating reflected (or scattered) uplight.

These different spatial light distributions are already difficult to interpret in the context of terrestrial light pollution. However, in terrestrial systems they can be supported by daytime albedo measurements because most land surfaces are diffuse reflectors (but not perfectly Lambertian). This means, that usually light is reflected at multiple angles and therefore the chance to be detected by a spaceborne sensor is high.

In contrast to terrestrial systems, the low albedo of water bodies and the directionality of the specular surface reflection impose further challenges for night-time remote sensing of ALAN in aquatic systems. Only a very small part of the light incident at a water body will reach a sensor looking down at nadir. Chances that no light is detected are much higher than for near-Lambertian surfaces. This results in water bodies appearing very dark in aerial images as can be seen in Figure 3 depicting a part of a night-time photograph of Calgary, CA, taken from the ISS. Most of the darkest pixels in the images are water bodies like the Bow River meandering through downtown. These are in stark contrast with the direct light emissions visible in the image. Thus, the dynamic range of night-time images comprising water bodies is much larger than during daytime. During the day, the sun illuminates the scenery and the upwelling radiation detected by the sensor depends mainly on the surface albedo. In the aerial data analyzed by Kuechly et al. (2012) the night-time dynamic range was several hundred, but the sensor also saturated.

Another challenge is the position and direction of the lamp. An example is sketched in Figure 6 showing two lighting scenarios with the same luminaire. The left scenario has the light from lamp A incident at the water body. As lamp A itself does not produce upwelling light and the water body does not reflect much light toward the zenith, lamp A will not be easily detected by an airborne or spaceborne sensor looking down at nadir. The scenario on the right side of the picture shows lamp B at the shoreline illuminating the ground but not the water. Lamp B has a higher chance to be detected by a spaceborne sensor, depending on the ground albedo. However, despite its vicinity to the water body, the direct impact onto the aquatic system itself could be minor if lamp B is properly designed. Still, lamp B could be a barrier or an attractor for other species such as aquatic flying insects at the aquatic terrestrial link (Manfrin et al., 2017; Meyer & Sullivan, 2013).

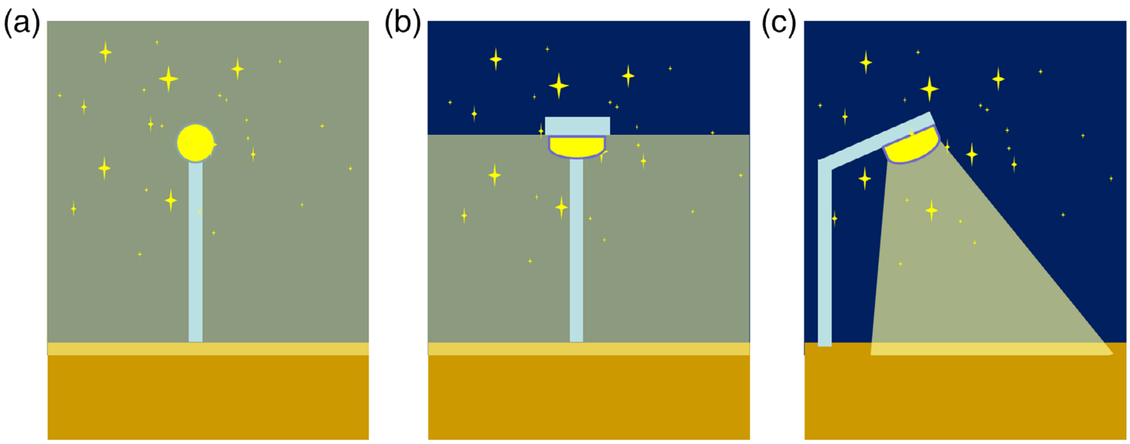

FIGURE 5 Sketch of different lamp types with different spatial emission patterns and uplight to downlight ratio

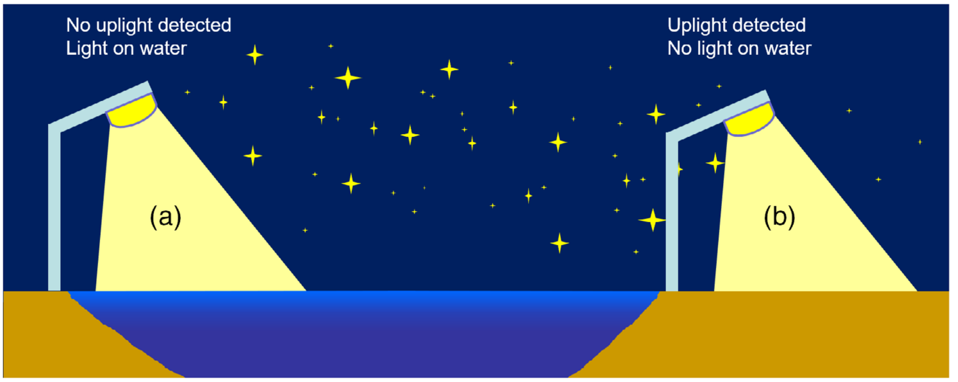

FIGURE 6 Two different shoreline lighting scenarios with the same luminaire

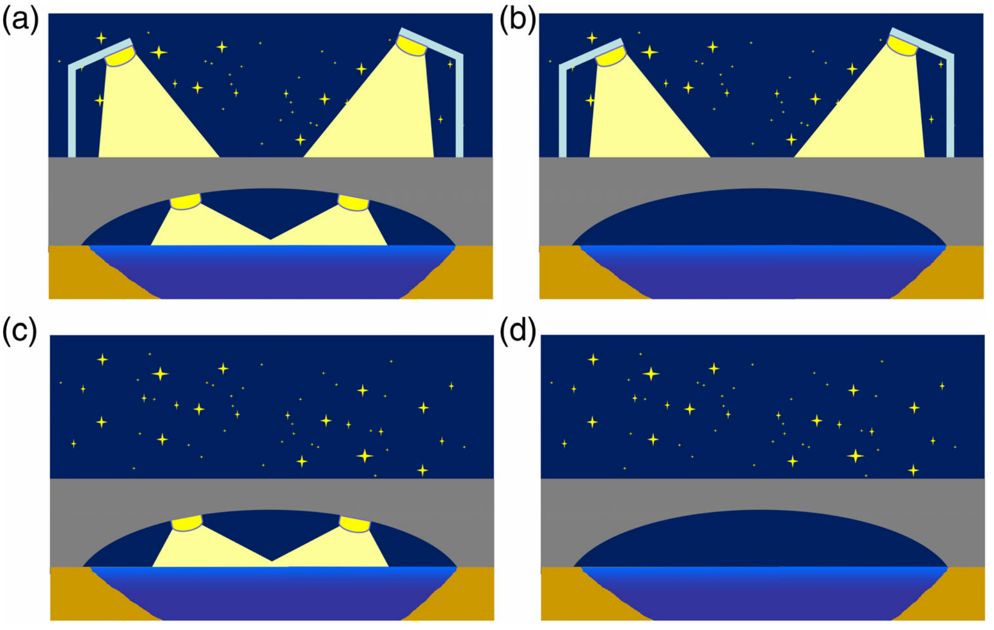

FIGURE 7 Sketch of differently illuminated bridges

As mentioned above (see Section 4.2), especially lit bridges can be important barriers for example, for migrating fish and lead to what is called a high landscape resistance. These bridges can be easily identified in the ISS image in Figure 3. However, it is not clear what the ratio between the light detected by the spaceborne sensor and the light incident at the water is. Four different scenarios are schematically depicted in Figure 7(a) a bridge lit above with uplight and with light underneath, (b) a bridge lit above with uplight and with no light underneath, (c) a bridge not lit above with no uplight and with light underneath, and (d) a bridge not lit above with no uplight and with no light underneath. From a spaceborne sensor, scenarios (a) and (b) from Figure 7 could appear identical, as well as scenarios (c) and (d). However, for underwater light pollution, scenarios (a) and (c) are identical and scenarios (b) and (d) could have no light entering the water.

These simple categories of course do not represent all real-world scenarios as can be seen on the example of a designer footbridge in Calgary, The Peace Bridge, shown in Figure 8a. This bridge has a complex lighting design and a mechanical structure that makes it difficult to estimate the ratio between upwelling and downwelling light. Figure 8b shows a zoom-in of the ISS image from Figure 3, where this bridge is clearly visible as a linear, lit structure that spans over the dark bending river.

5.2 | The need, the possibilities, and obstacles for in situ night-time light measurements

The problems with remotely sensed night-time light data in the context of aquatic light pollution discussed above (mainly Figures 6 and 7), corroborate the need for ground-based or underwater in situ data to evaluate the impact of ALAN on water bodies in general, freshwaters in particular and rivers most urgently. However, the amount of published in situ night-time light data for aquatic systems is scarce and the datasets are very hard to compare. These field measurements were performed with

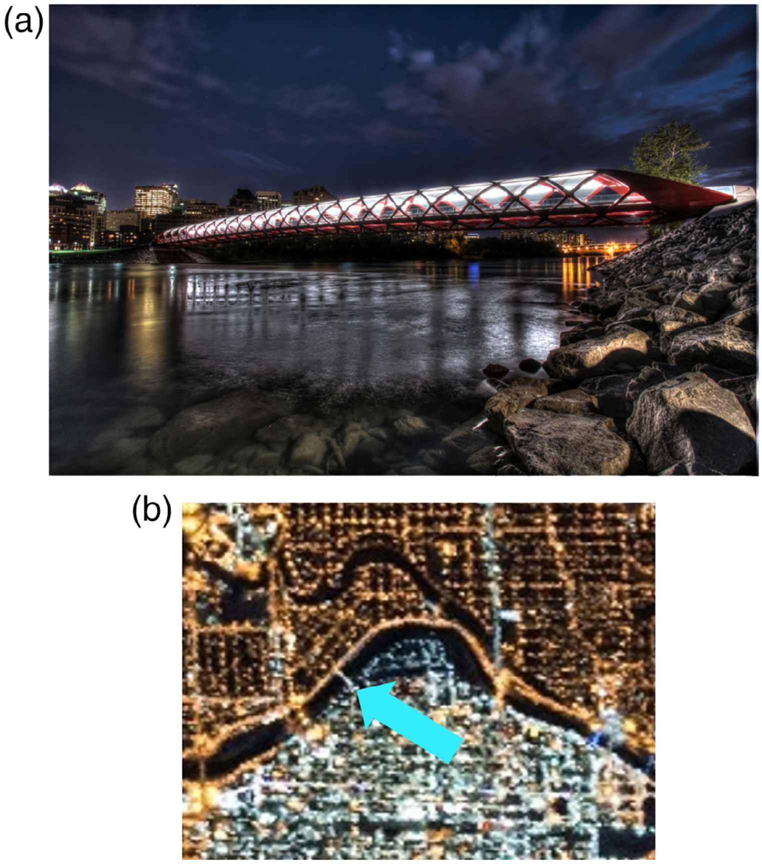

FIGURE 8 (a) High dynamic range image of a footbridge, Peace Bridge, in Calgary, Canada (image by Ryan Quan published under CC BY-SA 3.0), (b) a zoom in of the ISS image from Calgary, Canada, shown in Figure 3. The illuminated footbridge can be clearly seen from space (arrow)

many different instruments (luxmeters, spectrometers, SQMs, cameras) and different physical parameters were measured (spectral irradiance, illuminance, sky radiance at single point, spatially resolved sky radiance) at different positions (above the surface and below the surface). There is no clear coherence between these measurements, although each of them was well designed and conducted. One issue seems to be that very often the measurements were a secondary task and that the main interest was in ecological effects. Nevertheless, the existing work can serve as a good basis to design future measurement campaigns and layout a strategy for future routine or even automated measurements.

One key question is where to measure in the spatial domain. A comprehensive three-dimensional mapping of the underwater light field would highly be desired but is technically too challenging and time consuming at the moment. Tamir et al. (2017) have achieved such a mapping of downwelling multispectral irradiance (in 12 bands) in the clear waters of the Red Sea for 19 measurement points. However, the sensitivity of the device was limited to near shore or near surface measurements in these waters with high transparency. For turbid coastal or inland waters this method is not easily applicable due to the low light levels below the detection limit. Thus, a measurement in the horizontal plane appears most straightforward. For larger water bodies and especially rivers, transects or multipoint measurements are recommended (Ges et al., 2018; Jechow, Kolláth, Lerner, et al., 2017a; Ludvigsen et al., 2018; Tamir et al., 2017). Single-point measurements on multiple water bodies like performed by Secondi et al. (2017) are also reasonable especially in their context of small water bodies like ponds.

A fundamental decision is whether to map ALAN above or below the water surface. We recommend measuring above the water surface. Underwater measurements impose stronger requirements on the equipment regarding robustness (water-tightness, pressure etc.) and sensitivity. Light levels will decrease with depth, particularly in waters with high attenuation coefficients. Furthermore, cheap and very sensitive sensors for night-time light measurements are available from decades of research in terrestrial light pollution (Hänel et al., 2018) while most rigid underwater light sensors are designed for daytime measurements.

It is still possible to obtain the missing information about the light field below the surface by measuring spectrally resolved absorption coefficients by daytime light measurements or by obtaining them from water samples as shown by Secondi et al. (2017). Recent developments of shipborne systems show that it is possible to measure absorption coefficients "on-the-fly" for example by using the flow-through point-source integrating cavity absorption meter (ft-PSICAM) used on a system called "ferry box" in the Baltic Sea (Petersen, 2014; Wollschläger, Grunwald, Röttgers, & Petersen, 2013). When the absorption coefficients are known, the underwater light field can be modeled.

Another key question is which physical parameters should be measured and therefore which instruments should be used. Both directionality and spectrum are very important for aquatic ecology and for underwater light propagation modeling. Therefore, the measurement of a spatially resolved spectral radiance would be the ultimate choice to assess aquatic light pollution. In the best case, measurements above the surface and at different depths underwater would be obtained. The allrounder device capable of measuring this would be a very sensitive hyperspectral camera (ideally working even underwater) that can take images of the full hemisphere (or two to cover the whole sphere). Unfortunately, such a device does not exist at the moment and probably will not be available in the near future. However, we want to point out that hyperspectral imagers can be used under water even in the deep sea as shown with active illumination (Dumke et al., 2018). A single-point spectrometer scanning the hemisphere would be an alternative, but such a scan would be too time consuming for rapid transects.

As a single device for these measurements is not readily available, a multisensor approach must be developed. Summarizing the above discussion, the main strategy is to acquire spectral and directional information above the water surface. Spectral irradiance (preferred in the horizontal plane) can be readily measured at night-time with miniaturized spectrometers either above a reflectance standard as shown by Ludvigsen et al. (2018) in a very remote context or with a cosine corrector as shown by Secondi et al. (2017) in a more urban context. The directionality can be measured with cameras equipped with wide field optics, like fisheye lenses. Commercial DSLR cameras provide high-resolution raw images in three spectral channels and Jechow, Kolláth, Lerner, et al. (2017a) proved the applicability of such a system on a moving boat.

Figure 9a shows a sketch of the proposed platform setup using one hyperspectral sensor measuring spectral irradiance and three multispectral DSLR cameras with 180° fisheye lenses measuring the spectral radiance in three bands (RGB). The latter can be reduced to two cameras measuring in the vertical plane pointing toward the horizon or one all-sky camera pointing toward the zenith (Jechow, Kyba, & Hölker, 2019b). This approach allows comprehensively mapping of ALAN incident at the water surface. Underwater ALAN levels are then modeled based on this data when further information of the light attenuation in water is available. The recommended setup would also comprise a (profiling) absorption meter that measures the absorption coefficient of the water parallel to the night-time light measurements (Figure 9a). If such a setup is not available, data could be either acquired from daytime in situ light measurements with underwater spectrometers or from water samples following the procedure by Secondi et al. (2017). An interesting alternative could be remotely sensed data from multispectral (daytime) satellite measurements from platforms like Landsat-8, Sentinel-2 (Dörnhöfer, Göritz, Gege, Pflug, & Oppelt, 2016; Pahlevan et al., 2017) with 20–30 m resolution for smaller water bodies or Sentinel-3 (Toming et al., 2017) with 300 m resolution for larger inland waters and coastal regions.

A low-cost version of the measurement platform is shown in Figure 9b. This system uses single channel devices with neither spectral nor spatial information, such as luxmeters or sky radiance photometers like the SQM (normally pointing toward zenith). Such devices are less suitable for doing general light pollution surveys in aquatic contexts, but if the recommended

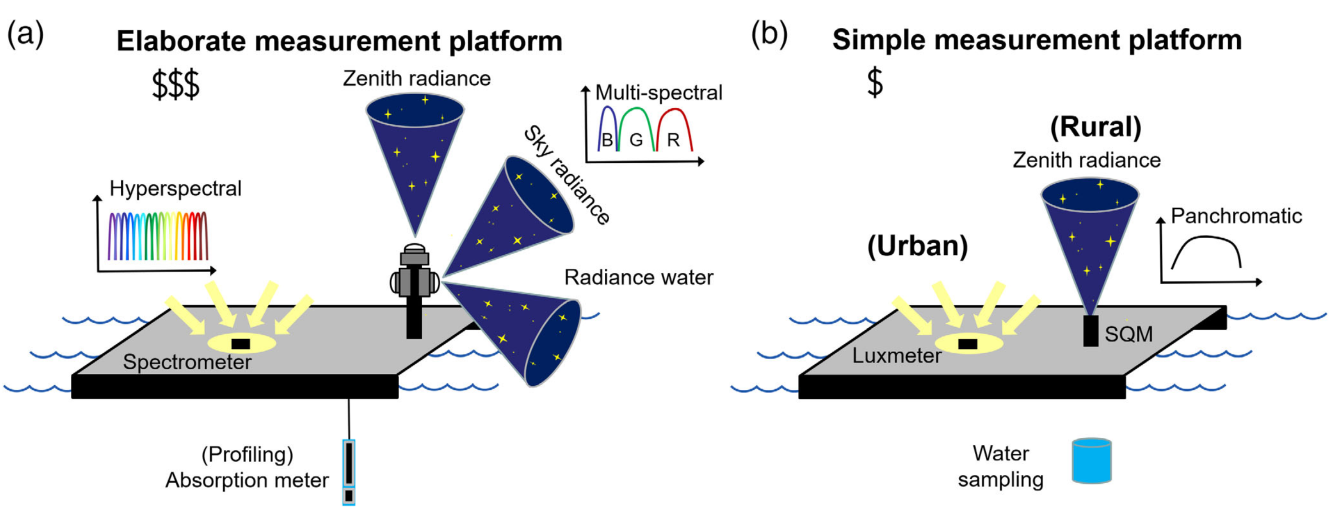

FIGURE 9 Sketch of (a) the proposed measurement platform and (b) a low-cost alternative

devices above are not an option, we recommend using luxmeters in urban contexts and for assessing direct light pollution, for example, from lit bridges and SQMs and similar devices for remote areas were skyglow is the main source of light pollution.

Whenever possible, a coupling of the ground-based measurements with high-resolution remote sensing data from astronaut photographs, aerial studies or upcoming satellite platforms such as Luojia 1-01 (Jiang et al., 2018) is recommended. If such data are not at hand, we recommend using at least VIIRS DNB data.

Future directions should include the development of more sensitive underwater and above water outdoor light measurement devices. This is technically challenging but feasible as very low light levels can be detected with single photon detectors or sensitive cameras in the laboratory (Jechow et al., 2013a; Jechow, Heuer, & Menzel, 2008; Jechow, Seefeldt, Kurzke, Heuer, & Menzel, 2013b; Streed, Jechow, Norton, & Kielpinski, 2012). Other future directions could include, for example, light polarization measurements as some aquatic species have shown sensitivity to polarization. For long-term trends and temporal as well as seasonal variation the installation of permanent monitoring stations is advised (e.g., from buoys using the platforms illustrated in Figure 9 with the minimum using an independent panchromatic zenith radiance sensor such as an SQM). In highly structured habitats or littoral zones it might be also necessary to better understand how complex structures such as bank vegetation, woody debris, rocks, or macrophytes affect the night-time light field of nocturnal habitats and may impact visual acuity and foraging efficiency as well as predator avoidance by aquatic organisms at night. This would require small-scale measurements that would be comparatively time demanding and technically challenging, but could be solved with autonomous underwater vehicles.

We want to point out that such ground-based measurements are important for inland and coastal waters and mainly for static light sources but are less applicable for the vast open ocean where fishing boats and other vessels are best tracked with remote sensing (e.g., Aubrecht et al., 2008; Fett, 1975).

6 | CONCLUSION

We have identified the major knowledge gaps in relation to missing night-time light data for assessing the impact of light pollution on aquatic ecosystems. By reviewing the state of the art of remote sensing technology and in situ night-time measurements as well their specific weaknesses and strengths, we conclude that it is best to perform ground-based night-time in situ light measurements, especially for smaller inland water bodies like rivers. For water bodies, the downwelling part of ALAN is the most important parameter to know, which is very difficult to estimate from remotely sensed data but can be measured in situ above and under water.

We recommend that research focuses upon

- measuring night-time light above the water surface,
- using a multisensor approach measuring downwelling spectral irradiance with a single-point spectrometer and spatially resolved multi-spectral (RGB) radiance with (multiple or at least one all-sky) 180° fisheye lens camera (Figure 9a),
- taking water samples and measure attenuation/absorption coefficients, ideally in real time with an underwater absorption meter
- modeling the underwater light climate based on light at night and water absorption measurements,
- performing transects or multipoint in situ light measurements,
- for a low cost alternative, using a luxmeter measuring downwelling horizontal illuminance in an urban context (direct light pollution) and a panchromatic zenith radiance measurement device like an SQM or alike in a remote (skyglow) context and,
- for long-term trends measuring from fixed buoys.

The integration of cross sensor approaches with remote sensing is advised, where new and emerging systems like ISS photographs or CubeSat platforms open up new possibilities for night-time studies. Future directions would be the development of underwater measurement devices with higher sensitivity, with an underwater hyperspectral 180° fisheye camera being the ideal device. Furthermore, the polarization of light at night should be measured above and under water. We further envision the use of autonomous underwater vehicles for three-dimensional surveys.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

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