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Light pollution from illuminated bridges as a potential barrier for migrating fish–Linking measurements with a proposal for a conceptual model

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ABSTRACT

Illuminated bridges have become important assets to navigable aquatic systems. However, if artificial light at night (ALAN) from illuminated bridges reaches aquatic habitats, such as rivers, it can threaten the river's natural heterogeneity and alter the behavioural responses of migratory fish. Here, via a pilot study, we quantified levels of ALAN at illuminated bridges that cross a river and, propose a conceptual model to estimate its potential implications on two migrating fish species with contrasting life histories. Night-time light measurements on the river Spree in Berlin were performed continuously along a transect and in detail at seven illuminated bridges. Photometric data of the pilot study showed rapidly increased and decreased light levels at several illuminated bridges from which we derived several model illumination scenarios. These illumination scenarios and their potential effect on migrating Atlantic salmon smolts (*Salmo salar*) and European silver eel (*Anguilla anguilla*) are presented as a conceptual model, considering illuminated bridges as behavioural barriers to fish migration. ALAN's adverse effects on freshwater habitats must be better researched, understood, managed, and properly communicated to develop future sustainable lighting practices and policies that preserve riverscapes and their biodiversity.

Introduction

Bridges are permanent landmarks that can cross navigable aquatic systems such as rivers, lakes, streams, canals and sometimes even parts of the sea. When located in urban areas, these structures often integrate lighting systems that span the gamut from functional to aesthetic illumination (Zielinska-Dabkowska, 2013). However, illuminated bridges can cause an impact of artificial light at night (ALAN) on aquatic habitats.

ALAN directly incident on a land or water surface is direct light pollution and can reach illuminances up to 1000 times brighter than during full-moon (Jechow & Hölker, 2019). Indirect light pollution originates from ALAN scattered in the atmosphere as skyglow, which creates light domes far beyond its source, depending on cloud cover and atmospheric conditions (Jechow et al., 2020). Because both direct ALAN and skyglow can reach aquatic realms (Jechow & Hölker, 2019; Smyth et al., 2021), it can cause a wide range of responses in freshwater organisms and thus present a threat to aquatic biodiversity (Hölker et al., 2023). For example, light pollution can alter diel vertical migration in zooplankton (Moore et al., 2000), disrupt drift in arthropods (Perkin et al., 2014a), and induce attraction (McConnell et al., 2010) or avoidance behaviour in fishes (Elvidge et al., 2018) and has been shown to disrupt dispersal in Atlantic salmon fry (*Salmo salar*) (Riley et al., 2015).

Bridge illumination can alter behaviour in bats (Barré et al., 2021) and insects (Nankoo et al., 2019; Szaz et al., 2015). For migrating fishes such as eel (*Anguilla anguilla)* and salmonids bridge illumination has been reported to interrupt their movements (Cullen & McCarthy, 2000; Lowe, 1952; Nightingale et al., 2006), and thus increasing the spatial resistance of a landscape. Consequently, migration may take more time and energy and impact the reproductive success of fish (Kurvers & Hölker, 2015). However, the mechanism by which the unnatural presence or absence of light (e.g. due to bridge structure or improperly managed ALAN) forms a behavioural barrier for fish migratory

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behaviour remains unclear.

To address this knowledge gap, we therefore, (i) quantified ALAN along a transect of the river Spree (Berlin, Germany) by continuous sky radiance and camera measurements at seven illuminated bridges. We then used this as a basis to (ii) identify different types of potential light barriers at illuminated bridges and estimate the potential effect of two light barrier types on fish migration behaviour by (iii) proposing a conceptual framework based on a literature review for vulnerable life stages of two migratory fish taxa with contrasting life histories — Atlantic salmon smolts (*S. salar*) and European silver eel (*A. anguilla*).

Materials and methods

The night-time measurements were performed during cloudy sky conditions on the 24th of February 2020 on a route of about 10 km from West to East (Fig. 1A) on the river Spree in Berlin (Germany) from an engine boat between ca. 19:30 and 21:49 local time (GMT +1), with the new moon setting at approximately 18:20 (GMT +1). At each bridge, we stopped at three points before, under, and after the bridge to measure in three directions with the camera. An all-sky image with the camera pointing towards the zenith, and two images in opposite directions with the camera imaging in the vertical plane, pointing towards the horizon, were obtained (Fig. 1B).

A calibrated digital single-lens reflex camera (DSLR, Canon EOS 6D)

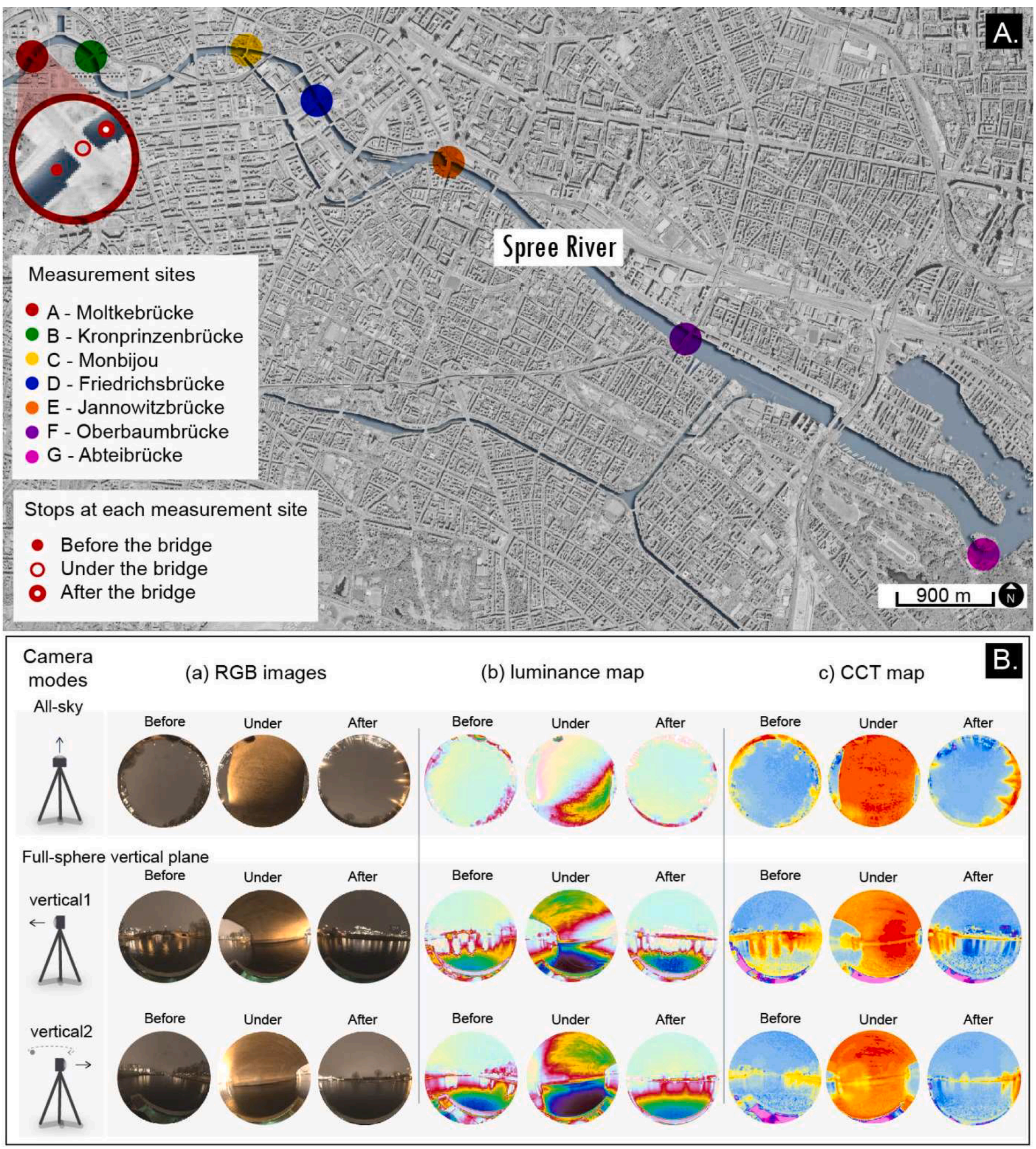

Fig. 1. (A) Map of the measurement sites, seven illuminated bridges along the river Spree in Berlin, Germany. At each bridge, measurements were performed at stops before, under and after the bridge. (B) At each stop, one all-sky and two vertical plane camera measurements were performed, from which the luminance map and CCT map were calculated. Example measurements from site A (Moltkebrücke) are shown in the full data set in the appendix.

with a wide-angle fisheye lens (Sigma EX DG $f = 8$ mm, F 3.5) with a 180° field of view was used to perform night-time light measurements. The camera measures the radiance in three spectral channels (red, green, blue – RGB). However, we relied on the Sky Quality Camera software (SQC, Euromix, Ljubljana, Slovenia) that utilises the green channel for a (near) photometric calibration. The software provides luminance, correlated colour temperature (CCT) maps (Fig 1B), and calculated illuminance. CCT is extracted by the software by transforming the three spectral channels (RGB) to CIE XYZ colour space. For details, see a recent review paper (Jechow et al., 2019). The camera was placed on a tripod to add stability as measurements were performed from a boat. The camera method is relatively precise, but the pointing error from the orientation and the movement and rocking of the boat induces an error of about 10 % (Jechow et al., 2017). ISO settings were fixed at 3200, and the shutter speed varied between 0.3 s at the darkest location and 1/13 of a second at the brightest location.

Additionally, the sky radiance at zenith was monitored continuously during the transect with a mobile night-sky radiometer equipped with a data logger (Sky Quality Meter, SQM-LU-DL, Unihedron, Ontario, Canada) in magnitude per square arc second, $mag_{SQM}/arcsec^2$, which is a negative logarithmic unit, where low values represent high radiance, and high values represent low radiance. Furthermore, a difference of 2.5 is a factor of 10 in the linear scale, and a 5 magnitude difference is a factor of 100. A rough approximation of luminance can be done using $L_v \approx 10.8{\cdot}10^4{\cdot}10^{(-0.4\cdot mag_{SQM})}$, but it must be treated cautiously.

A clear night sky reference is about 21.6 $mag_{SQM}/arcsec^2$ (approximately 0.25 mcd/m^2) (Hänel et al., 2018). The primary GPS device, intended to record boat position, failed. Thus, positions had to be estimated with a second camera (Canon EOS 6D with a 50 mm lens) equipped with a GPS on the boat to record images of the illuminated locations around the measurement sites.

Results

From the luminance data of the all-sky images, horizontal illuminance and the two opposing vertical plane images of total spherical scalar illuminance were calculated. The full imaging dataset (see Appendix A), and the illuminance results are summarised in Tables 1 and 2. Fig. 2A shows the horizontal illuminance, and Fig. 2B the scalar illuminance for each site, showing a gradual decrease along the transect for horizontal illuminance and slightly more heterogeneity but the same trend for scalar illuminance. At most bridges, the lowest values in illuminance were measured under the bridge, except for measurement site A – Moltkebrücke, the only bridge lit underneath. Thus, at Moltkebrücke, the highest horizontal illuminance (ca. 1100 mlx) was measured under the bridge compared to the other six measurement sites (170 mlx to 9 mlx). The lowest illuminance under the bridge, of only 9 ± 1 mlx, was measured at site E (Jannowitzbrücke), which is ca. 120 times darker than site A (Moltkebrücke). Furthermore, the maximum illuminance ratio (R_{max}) was determined by dividing illuminance under the bridge by the highest illuminance obtained before or after the bridge to illustrate the largest step in light level change from open waters to the bridge or vice versa, shown in Table 1. The R_{max} values ranged from 0.88, indicating brighter conditions under the bridge (A – Moltkebrücke) to 105, indicating darker conditions under the bridge (E – Jannowitzbrücke), showing the strong heterogeneity amongst these bridges.

Table 1
R_{max} of horizontal and scalar illuminance obtained from the multispectral imaging data at three stops on Measurement sites A – G. R_{max} is determined by dividing illuminance under the bridge by the highest illuminance obtained before or after the bridge. It represents the maximum illuminance ratio and the largest step in light level change from open waters to under the bridge or vice versa.

Measurement sites	Horizontal illuminance E_v (*all-sky*) (mlx) R_{max}	Scalar illuminance $E_{v,\ scal}$ (*vertical 1 and vertical 2*) (mlx) R_{max}
A	0.88	2.1
B	5.9	2.8
C	11.4	3.9
D	12.5	4.7
E	105	12.8
F	21.3	8.2
G	1.3	1.4

The scalar illuminance was always lowest under the bridge when comparing all site measurements (positive R_{max}). The R_{max} values ranged between factors of 1.4 (G – Abteibrücke) to 12.8 (E – Jannowitzbrücke), giving a smaller range than for horizontal illuminance.

The continuous sky radiance measurements obtained along the transect with the SQM are shown in Fig. 3. The bridges can be identified as rapid changes in sky radiance (or radiance above the boat as direct or straylight will also be picked up by the sensor, and creates extraordinarily high readings). Skyglow over the transect ranged from approximately 14 $mag_{SQM}/arcsec^2$ in the urban zone (ca. 270 mcd/m^2, about 1000 times brighter than a reference clear sky) to 17 $mag_{SQM}/arcsec^2$ (ca. 17 mcd/m^2) towards the peri-urban area.

Direct ALAN was present at the bridge – Mühlendammbrücke (site 12 in Fig. 3) and at the locks – Mühlendammschleuse (site 13, in Fig. 3), which creates radiance values of approximately 10–12 $mag_{SQM}/arcsec^2$ that cannot be used quantitatively because it is unclear what is the contribution of direct ALAN, straylight or real sky radiance. Under most bridges, a reduction in radiance occurred. However, radiance was increased at measurement site A – Moltkebrücke (site 1 in Fig. 3 and Appendix A) and several other lit bridges (sites 3, 6, 19 in Fig. 3). Radiances at these lit bridges reached 12 $mag_{SQM}/arcsec^2$. At one bridge, Ebertbrücke (site 6 in Fig. 3), only increased radiance was observed, indicating that the bridge was lit underneath. Interestingly, a reduction of radiance was observed at the three other lit bridges. At Moltkebrücke (site 1 in Fig. 3), the bridge was lit underneath, and the bridge illumination did not cover the whole arch and left a dark section. At the other two lit bridges, Marschallbrücke (site 6 in Fig. 3) and Abteibrücke (site 19 in Fig. 3), an increase of radiance was observed before and after the bridge most likely caused by spill light from road lighting intended to illuminate the bridge above.

Sky radiance variations of two measurement sites with contrasting sky radiance values occurring when approaching the bridge are shown in Figs. A8 and A9 (see Appendix A). Measurement site A – Moltkebrücke exhibits uninterrupted skyglow along the river transect, which becomes brighter as the boat passes under the bridge, subsequently darkens, and then rather rapidly returns to the skyglow radiance values after crossing the bridge (see Fig. A8). Luminance maps of Moltkebrücke shown in Fig. A1 (see Appendix A) confirm that one half of the underpath is illuminated, while the other half is not. Meanwhile, measurement site E – Jannowitzbrücke shows a consistent skyglow over the river transect, which is reduced in radiance as the boat reaches the bridge. The attenuation of skyglow becomes pronounced under the bridge as no luminaires were observed at the underpath and due to the bridge's width, confirmed with the luminance maps shown in Fig. A5 (see Appendix A). Subsequently, after crossing the bridge, the darker section under the bridge rapidly returns to skyglow radiance values. The exact function how rapidly the level changes could not be obtained and would require a higher temporal resolution (and/or finer spatial resolution, respectively) of measurement.

Conceptual framework of light barriers

This section proposes a conceptual framework for illuminated bridges as barriers potentially impacting fish migration. From the measurement data, several bridge illumination types depend on the surrounding skyglow and the illumination under the bridge. As no comprehensive data on light colour was obtained, the conceptual framework focuses only on the changes detected by the SQM.

In this context, a light barrier is described as an encountered dark-to-

Table 2
Horizontal and scalar illuminance obtained from the multispectral imaging data at three stops on Measurement sites A – G. Stops *before* and *after* were obtained proximate to the bridge's edges. Stop *under* was obtained under the bridge.

Measurement sites	Horizontal illuminance E_v (*all-sky*) (mlux) R_{max}				Scalar illuminance $E_{v,\ scal}$ (*vertical 1 and vertical 2*) (mlux) R_{max}			
	Stops at the bridge			R_{max}	Stops at the bridge			R_{max}
	Before	Under	After		Before	Under	After	
A	970	1100	1040	0.88	2340	1630	3380	2.1
B	950	160	940	5.9	3420	1240	3180	2.8
C	910	80	800	11.4	2750	700	1660	3.9
D	710	60	750	12.5	1960	450	2130	4.7
E	730	9	950	105	2230	220	2810	12.8
F	640	30	630	21.3	2380	290	1960	8.2
G	220	170	220	1.3	660	630	870	1.4

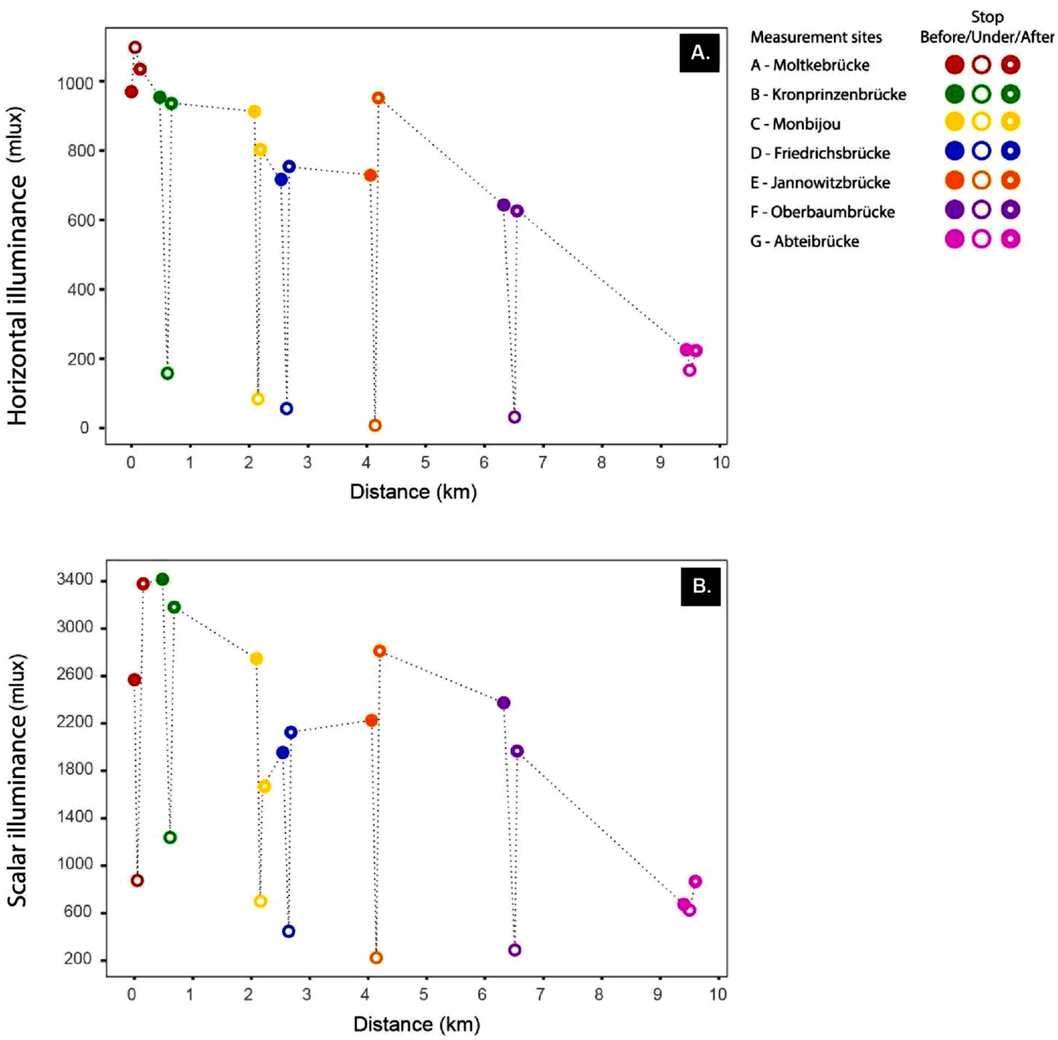

Fig. 2. Photometric data obtained from the A – G measurement sites with all-sky camera mode at three different stops: before, under, and after the bridge (see Fig. 1B). (A) Horizontal illuminance as a function of distance. (B) Scalar illuminance as a function of distance.

bright (a positive step function) or bright-to-dark section (a negative step function) when passing under a bridge. This conceptual framework considers only one parameter of light — its brightness (light levels). The conceptual framework highlights an example of light step functions (Fig. 4) and light step functions resulting from each bridge illumination type (Fig. 5). These are linked to potential behavioural responses of migrating fish (Fig. 7).

Light step functions and bridge illumination types

Fig. 4 (A - C) shows imaging measurement data (luminance maps) of Jannowitzbrücke. The bridge is unlit underneath, and the surroundings show strong direct and indirect ALAN. Thus, the illuminance under the bridge (Fig. 4B) is much lower than before and after the bridge (Fig. 4A, C; see also Table 1). Therefore, illuminance decreases when moving from the open waters towards the underpath of the bridge, representing a negative light step function; when moving from the underpath of the bridge towards open waters, illuminance increases, which represents a

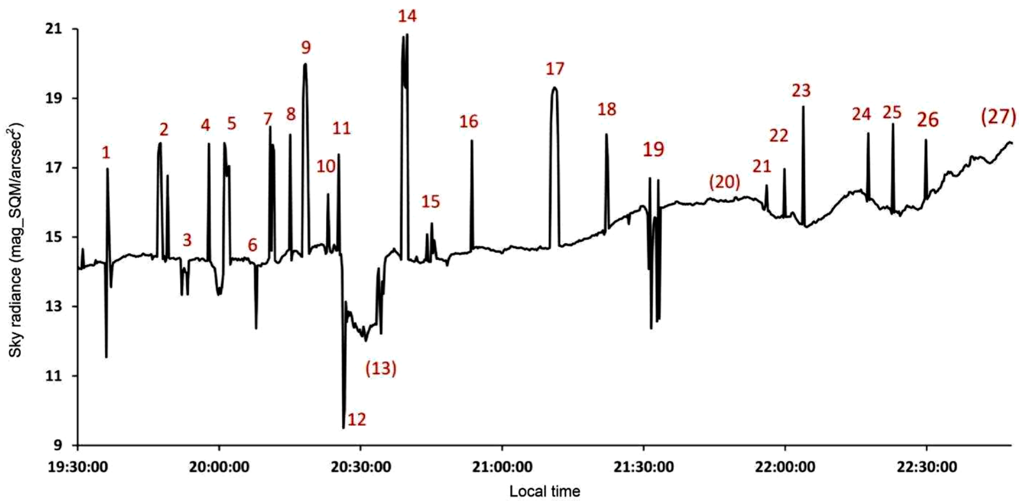

Fig. 3. Continuous sky radiance SQM measurements while the boat moved along the transect. Note the negative logarithmic scale (see Methods). Bridges are perceivable as rapid changes in radiance and indicated with numbers (numbers in brackets indicate ALAN-specific sites that are no bridges): 1- Moltkebrücke, 2 - Kronprinzenbrücke, 3 - Marschallbrücke, 4 - Bahnhof Friedrichstraße, 5 - Weidendammer Brücke, 6 - Ebertbrücke, 7 - Monbijoubrücke, 8 - S-Bahn Brücke Hackescher Markt, 9 - Friedrichsbrücke, 10 - Karl-Liebknecht Brücke, 11 -Rathausbrücke, 12 - Mühlendammbrücke, (13) - Locks Mühlendammschleuse (direct ALAN), 14 - Jannowitzbrücke, 15 - Michaelbrücke, 16 - Schillingbrücke, 17 - Oberbaumbrücke, 18 - Elsenbrücke, 19 - Abteibrücke, (20) - Plänterwald (no ALAN), 21 - Minna-Todenhagen-Brücke, 22 - Alte Stubenrauchbrücke, 23 - Treskowbrücke, 24 - Wilhelm-Spindler-Brücke, 25 - Dammbrücke, 26 - Salvador-Allende-Brücke, (27) - Müggelsee (no ALAN).

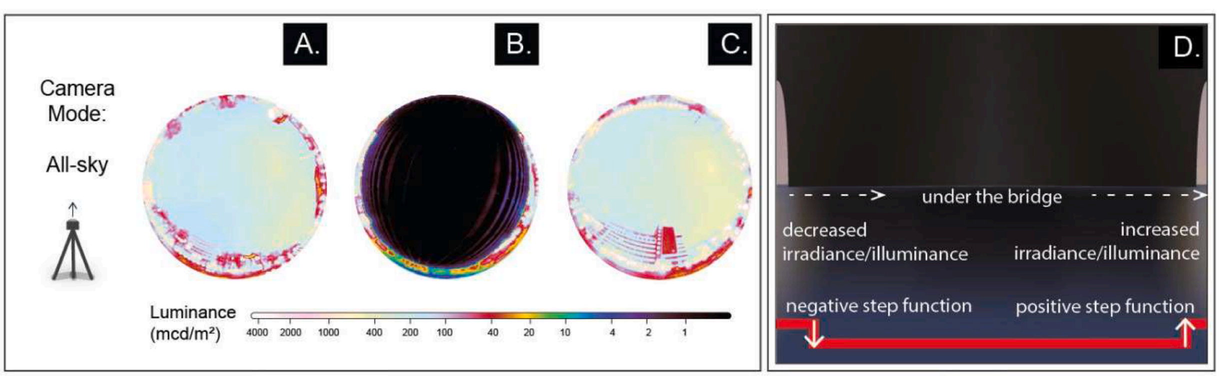

Fig. 4. (A - C) Luminance maps for stops (A) before, (B) under, and (C) after the bridge at measurement site E – Jannowitzbrücke. The all-sky luminance maps of Jannowitzbrücke exhibit higher luminance in open waters (A, C) when compared to luminance levels under the bridge (B). (D) Cross-section of the bridge arch structure that exhibits changing light step functions (when moving from left to right) when crossing from open waters towards the underpath of the bridge and again to open waters. A decrease in irradiance or illuminance indicates a negative step function, and an increase in irradiance or illuminance indicates a positive step function.

positive light step function (Fig. 4D).

R_{max} represents the change in illuminance of the step function (see Table 2), with values below 1 indicating a negative step function and above 1 indicating a positive step function when moving from the brightest location outside the bridge towards underneath the bridge.

Four bridge illumination types were derived from camera and SQM measurements and previous work by Jechow and Hölker (2019). These bridge illumination types were simplified to consider only illumination above (roadway illumination) and underneath the bridge (underpath illumination).

Depending on the location of the bridge (e.g. surroundings and the light pollution context), the illuminated bridge will form a potential light barrier composed of multiple negative or positive step functions. Fig. 5 illustrates a cross-section and a side view of eight illuminated bridge scenarios. Four simplified bridge illumination types are set in rural areas with no skyglow (Fig. 5A - D). The other four simplified bridge illumination types are set in urban areas with skyglow (Fig. 5E - H). Real-world bridge illumination types and scenarios will depend on the geometry of the bridge and light levels, which can be very heterogeneous, consisting of skyglow, light spill from roadway illumination, architectural or functional lighting underneath and towards the bridge vertical surfaces, and direct ALAN sources located proximate to the water that often include advertisements, windows, lit building surfaces, light from adjacent roads or parks, etc. (Pérez Vega et al. subm.)

ALAN and migrating fish

It is important to interpret the bridge illumination types with their light step functions as potential barriers for migrating organisms.

ALAN can aggregate and slow down migratory fish species. It has been previously reported that some salmonids and eels occasionally interrupt their migration at lit structures (Lowe, 1952; Cullen & McCarthy, 2000; Nightingale et al., 2006; Riley et al., 2012, 2013). ALAN, particularly at bridges, may thus increase the spatial resistance of a landscape. Consequently, migration can take more time and energy, which could threaten natural synchronous reproduction and reproductive success (Kurvers & Hölker, 2015). However, it remains unclear whether bridge illumination is a behavioural barrier that disrupts fish

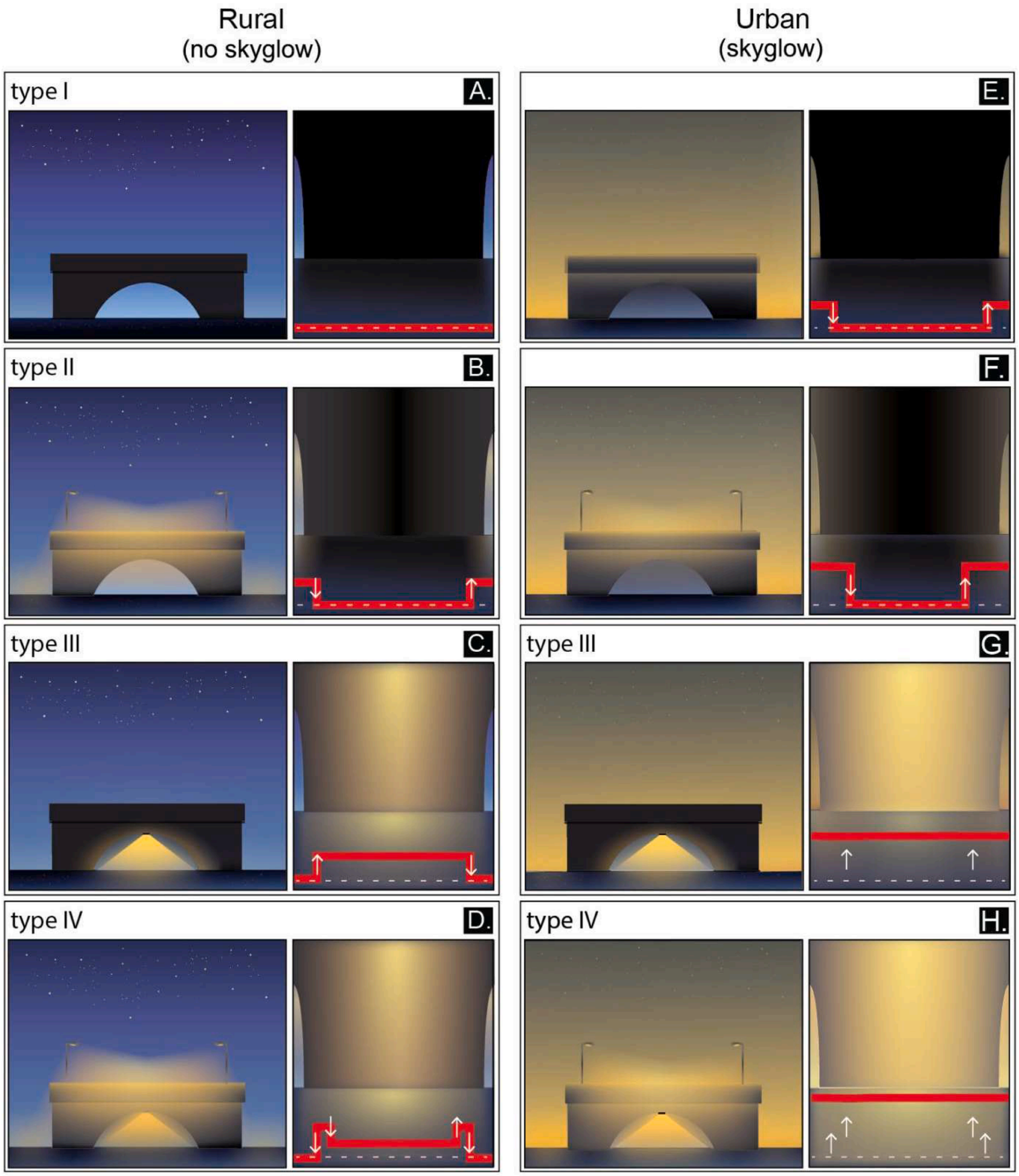

Fig. 5. Side views and cross-sections of eight bridge illumination scenarios spanning (A - D) rural and (E - H) urban rivers. The side views show the perspective of the bridge as seen from a boat when approaching an arch. The cross-section shows the underpath of the bridge. The dashed lines represent the expected natural light levels typical in a river with a bridge. The red lines represent the varied levels of irradiance or illuminance of different illuminated bridge scenarios, which form multiple potential light barriers originating from multiple positive and negative light step functions, except for bridge illumination types (A) and (G). The white arrows highlight steps in illuminance/irradiance. (A, E) Type I has an unlit roadway and underpath. (B, F) Type II has an illuminated roadway and unlit underpath. (C, G) Type III has an illuminated underpath with no roadway illumination. (D,H) Type IV has roadway and underpath illumination (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

migration. Furthermore, a fish's response to a positive or negative light step function is likely to depend on the fish's life history. In the scenarios mentioned above, positive and negative light step functions might alter the information a migrating fish requires to accomplish its migration.

Migration is often defined as an adaptive and seasonal long-distance movement in a species' life cycle. It is also derived from the spatial and temporal distribution of resources and environmental conditions to breed, forage or find favourable climatic conditions (Smith, 2012; Myers, 1949; Dingle & Drake, 2007). Fishes like salmon smolts and eels migrate through various connected aquatic systems (Hasler, 1956; Aarestrup et al., 2009). However, eels and salmon have developed distinct migration strategies, which have resulted in very different combinations of behavioural and reproductive traits.

For example, eels are anadromous, i.e. they spend their adult life in freshwater and return to the sea to reproduce. They often migrate during fall, winter, rain or flooding events that might increase river flow and at night, when light levels are often low (Haraldstad et al., 1985; Hadderingh et al., 1999; Van den Thillart et al., 2009). During migration, eels tend to swim in deeper parts of the water column and have been observed to avoid illuminated waters at night (Haraldstad et al., 1985; Van den Thillart et al., 2009). Salmon, on the other hand, are catadromous, migrating from the sea to freshwaters during the day or at night in spring and autumn. Their nocturnal migration usually is closer to the water surface, and active behaviour, including positive phototaxis, has been observed near illuminated waters (Shapovalov, 1941; Antonsson & Gudjonsson, 2002).

Fig. 6 provides an overview of demonstrated behavioural responses in eels and salmon upon exposure to ALAN and natural light, respectively. During their migration, eels and salmon are often exposed to unique optical aquatic environments modulated by turbidity, the presence of dissolved organic matter and further absorbing substances, and illuminated waters at night (Johnsen, 2012; Elvidge et al., 2018; Jechow & Hölker, 2019; Hölker et al., 2023).

Bridge illumination as a behavioural barrier

The potential implications of light barriers on the migration strategies of silver eels and salmon smolts can include a pitfall effect — where fish are retained in a small area, resulting from their responses to light stimuli. However, the behavioural mechanisms driving this potential effect vary between salmon smolts and silver eels.

Naturally dark environments are ideal for successful eel migration (Fig. 7A) due to their preference for low light levels (Durif et al., 2000). Any scenario in which light is introduced into the water column can potentially induce avoidance behaviour in eels (Fig. 7B, D) (Elvidge et al., 2018; Vowels & Kemp, 2021; Hadderingh et al., 1999; Cullen & McCarthy, 2000). Furthermore, dark areas bounded by light may induce a pitfall effect (Fig. 7C), behaviourally constraining eels to the dark

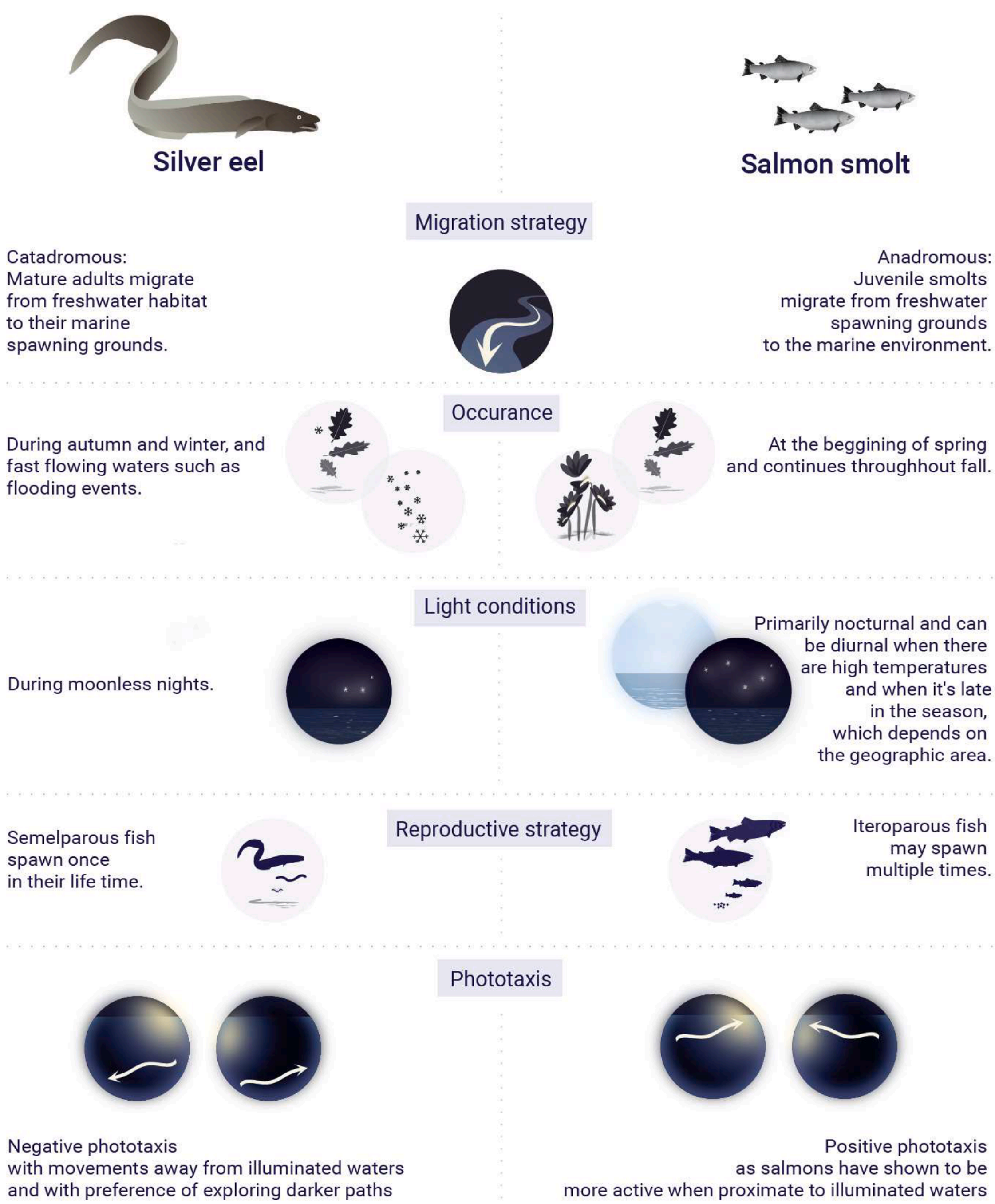

Fig. 6. A summary of the contrasting migration behaviours of silver European eel and Atlantic salmon smolt.

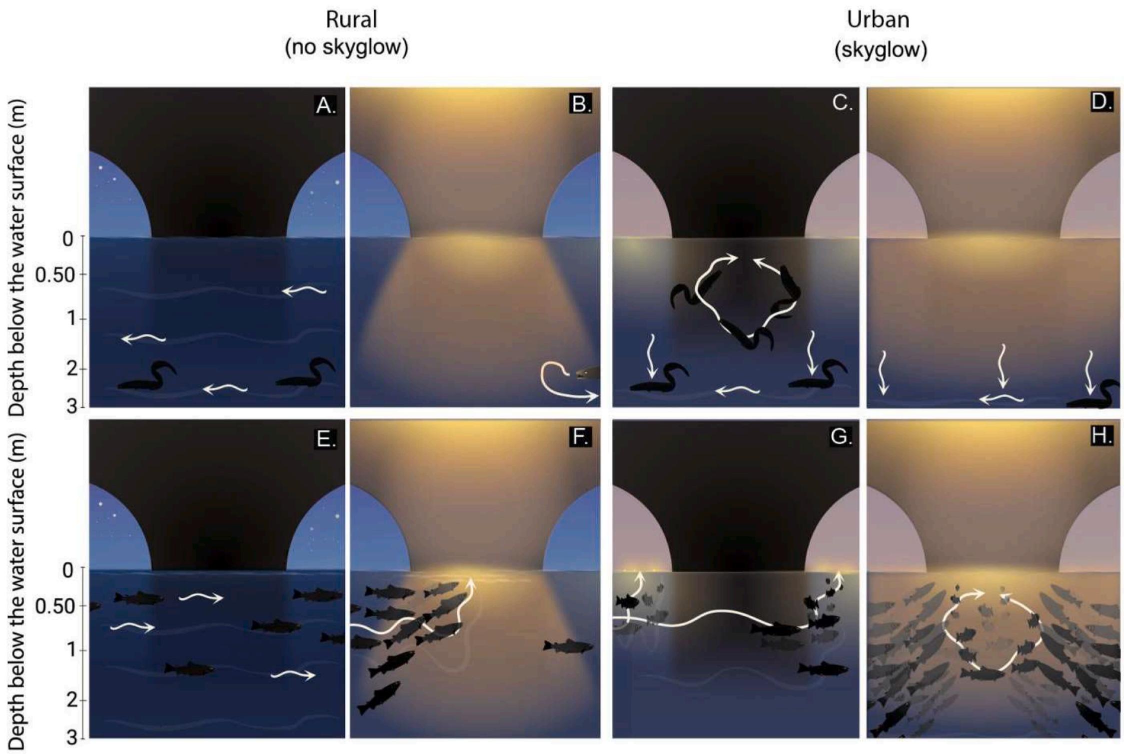

Fig. 7. (A - H) An overview of the expected behavioural responses to bridge illumination in two selected species, silver European eel and Atlantic salmon smolt. The two selected species represent vastly different life histories and migration behaviours. (A - D) During migration, eels have been shown to remain at the far end of the water column and have been observed to avoid illuminated waters at night. (Lowe, 1952; Cullen & McCarthy, 2000; Vowles et al., 2021). (A) During their migration, Silver European eels can eventually reach their marine spawning grounds when navigating rivers with naturally low light levels at night. However, (B - D) if unnatural contrasting light scenarios at illuminated bridges are encountered, their migratory behaviour could be delayed, which can (B) change their migratory direction, (B) force eels to remain under dark paths (e.g. under unlit bridges), (D) orientate eels closer to the bottom of the water column. (E - H) Meanwhile, Atlantic salmon smolts have been shown to migrate at night closer to the water surface with active behaviours when proximate to illuminated waters (Shapovalov, 1941; Ali, 1962; Antonsson & Gudjonsson, 2002). (E) They can eventually reach their freshwater spawning grounds when navigating waters that remain under naturally low light levels at night. However, if Atlantic salmon smolts encounter unnatural contrasting light scenarios at illuminated bridges, their migration could be altered or delayed due to their potential attraction to ALAN. This behaviour can potentially drift them away from their migratory paths into (F) illuminated corners under the bridge, (G) urban light polluted areas in the vicinity, or can possibly (H) trap and aggregate Atlantic salmon smolts in illuminated waters.

underpass of a bridge for some time. Lastly, as ALAN can attenuate rapidly with water depth, illuminated bridges may push migrating eels to the bottom of the water column as they pass (Fig. 7D).

Contrastingly, Atlantic salmon smolts can exhibit positive phototaxis, where ALAN exposure causes attraction and aggregation in illuminated areas (Tétard et al., 2019). In the case of the illumination scenarios with underlit bridges (Fig. 7F, H), attraction to ALAN may result in a pitfall effect, causing smolts to aggregate directly under the bridge. Lastly, illumination scenarios with high levels of urban skyglow and unlit dark underpass may also present a barrier to migration (Fig. 7G). Ono and Simenstad (2014) observed that daytime shadows cast by overwater structures obstructed the outmigration movements of juvenile Salmon (*Oncorhynchus* spp.).

Discussion

River systems are often modified by natural and anthropogenic drivers that can lead to fragmentation or reduction of river heterogeneity (Fischer & Lindemayer, 2007). Given the benefit illuminated bridges contribute to night-time route connectivity, their ecological impact is rarely questioned. To better understand the potential anthropogenic impacts on a river ecosystem, it is important to take a look at the pristine state of the Spree river prior to human settlement.

The historical landscape of the Spree river was characterized by riverbanks with adjacent floodplains and densely forested areas (Nützmann et al., 2011). Today‘s river landscape, however, bears little resemblance to its original state and often gives the impression of an urbanized waterway modulated by multiple stressors that challenges aquatic communities. The results of this study demonstrated that the river Spree in Berlin is heavily exposed to one of these urban stressors – ALAN, which is characterized by sky radiance variations (skyglow), ALAN gradients, and steep light contrasts. Illuminated bridges can thus cause novel types of nocturnal light by generating excessive light levels, limiting natural darkness and thus producing light contrasting ratios at rivers unprecedented in evolutionary history.

The continuous sky radiance and single-point illuminance measurements showed that the proximity to urban elements (e.g. bridge structures), the composition of the bridges, and their integrated lighting systems can shift the light environment in a river. Skyglow (i.e. sky radiance) on the Spree was high due to cloudy skies (see also Jechow et al., 2020), with the highest values measured in the (urban) center and a gradual decrease of skyglow (compared to the rapid changes in radiance observed at the bridges, the sharp peaks in Fig. 3) towards the less densely populated eastern part of Berlin was observed. The decrease in sky radiance was not following a strict inverse power law, but rather also showed local increase when being close to a sub-urban centre (i.e. Berlin-Schöneweide near Treskowbrücke – 23 in Fig. 3 or Berlin-Köpenick near Dammbrücke – 25 in Fig. 3). This showed that the level of urbanization is not only linked to direct emission but also the skyglow background (Jechow & Hölker, 2019). The sky radiance values align with studies performed in Berlin in a terrestrial context (Jechow et al., 2020), where about the same elevated sky radiance and illuminance levels for cloudy skies were found. Furthermore, the change of sky radiance with distance from the urban centre were shown to differ inside and outside the city limits, particularly for cloudy skies (Jechow et al., 2020). In the same study, clear sky measurements were performed at the same locations showing much lower but still elevated values. Repeating our measurements under clear conditions would have most likely resulted in a different skyglow background. However, COVID lockdown in Germany had closed river locks (Jechow & Hölker, 2020) and banned us from repeating this transect in time.

In general, measurements in freshwater systems are sparse (Jechow & Hölker, 2019); the only longer-term but static sky radiance measurements were done on a lake (Jechow et al., 2016). Analyses of nocturnal aerial photographs of Berlin show rivers and canals approximately six times brighter than lakes due to their large ratio of shore length to the water surface (Kuechly et al., 2012) and a multi-point study at Berlin waters using a precise underwater lux metre showed that illuminance ranged between 0.008 lx and 1.4 lx at 0.5 m below the surface (Perkin et al., 2014b).

It is difficult to disentangle the fractions of skyglow and direct ALAN from our measurements. However, in urban areas, the use of multi-spectral (RGB) all-sky images with a digital camera provides spatially resolved luminance maps over the complete hemisphere in three spectral bands in one image by a single measurement. It involves the light field information from all directions (horizontal illuminance and two opposing vertical plane images of total spherical scalar illuminance). With the use of this method, the results demonstrated lower values under most bridges, except for measurement site A – Moltkebrücke, and that the Spree river was prone to divergent light scenarios. Nevertheless, our data showed that a finer spatial resolution of direct ALAN measurements would be beneficial.

As discussed above, our measurements fit previous data obtained in Berlin central area under cloudy conditions (Jechow et al., 2020). Given the varying sky radiance (skyglow), ALAN gradients, and steep light contrasts, it is important to relate the potential effects of different lighting situations on migrating fish. Thus, a conceptual framework is proposed to outline the multiple behavioural mechanisms that may delay fish migration in rivers with bridge lighting and to describe the impact of illuminated bridges as behavioural barriers for migratory aquatic species.

Although migratory delay caused by a single bridge may appear minor, urban migratory paths often consist of multiple illuminated bridges of varying types, which can potentially cause a large cumulative delay in migration. Understanding how variance in bridge illumination types and behavioural responses affects these delays is critical to estimate the cumulative impacts and potential fitness consequences. While little is known about the effect of migration timing on eel spawning, the river phase of this migration is discontinuous — involving expanded stopovers (Stein et al., 2016) and a few periods of locomotion, generally initiated by high discharge and low light conditions (Durif et al., 2000). In the absence of favourable migration conditions, eels have been reported to postpone migration to the following year (Vøllestad et al., 1994) and silvering — the physiological and morphological changes associated with sexual maturation — is assumed to reverse (Svedäng & Wickström, 1997). For migration routes with multiple illuminated bridges, cumulative migration interruptions resulting from ALAN exposure may be sufficient to trigger migratory postponement. Lastly, as eels tend to migrate when turbidity is high and under low light levels (Durif et al., 2000), and being negative phototactic during nocturnal migration (Vowles & Kemp, 2021), the propagation of ALAN into the lower part of the water column may cause eels to orientate even closer to the bottom or to become inactive. Therefore, illumination on bridges needs to be better shielded and reduced to low light levels, in order to mitigate the impact on eels.

In contrast, Atlantic salmon smolts may exhibit positive phototaxis when exposed to ALAN. This effect of smolt attraction to ALAN can be considered multi-faceted. First, the survival of smolts upon arrival in the sea is proposed to be dependant on the timing of arrival during the smolt window (Rikardsen et al., 2004; McCormick et al., 1998) — a short period where environmental conditions facilitate the rapid growth critical for their survival to the post-smolt stage. A delayed arrival in the sea may result from attraction to ALAN, negatively impacting the smolt's fitness. Secondly, migrating smolts are highly sensitive to predation. Predatory fish have been shown to aggregate towards ALAN, corresponding with higher predation rates of migrating salmonid smolts (Nelson et al., 2021). The pitfall effect illuminated bridges can have on smolts may prolong their exposure to high-predation areas during migration, reducing survival. Thus, also for smolts, bridge illumination would need to be better shielded and reduced to low light levels to mitigate impacts.

Lastly, all teleost species accomplish visual adaptation between light and dark conditions with retinomotor movements — movements of the rod, cone, and epithelial pigment cells within the retina (Burnside et al., 1983). While the time required for adaptation varies by species, life stage, and light levels, juvenile Atlantic salmon have been shown to require more than 25 min to adapt between light to dark conditions (Ali, 1962). During this adaptation period, the fish may be unable to perceive crucial information about their environment, such as the presence of predators, and consequently, the ability to execute visually-mediated predator avoidance responses. Hence, adaptation to bridge illumination conditions may reduce fitness due to an increased and prolonged predation risk.

To date, the ecological status of a river such as the Spree accounts for the impact induced by human use associated with dams, locks, water mills, fish weirs, navigation, industrial pollutants, and human recreation (Dudgeon et al., 2006). The impact of illuminated bridges over rivers still remains understudied. Studies have shown that riverine wildlife, including insects and bats, can be affected by bridge illumination as their flying paths are interrupted by bridge ALAN (Barré et al., 2021; Nankoo et al., 2019; Szaz et al., 2015). Therefore, more studies are required to determine bridge ALAN as a potential light barrier likely to alter the passage of species on riverine systems. Bridge architectural forms such as the beams, the truss, the arch, the suspension, the cantilever, and the cable stay, as well as reflectance of materials (e.g. stainless steel, white paint) could play an important role in the complexity of light distribution over the river. Therefore, illuminated bridges, or structures that cross any form of a natural waterbody, need to be studied in detail to identify light conditions that can potentially have negative impacts on migratory species in order to deliver recommendations that avoid ecological hazards. Future ALAN research should focus on the implications of ALAN on freshwater systems as rivers are an integral part of the urban realm in which light barriers can adversely affect freshwater habitats and biodiversity hotspots. More ALAN research could aid prevent the loss of nocturnal integrity in freshwater systems (Hölker et al., 2023).

The conceptual framework presented here, proposes a simplified model of how potential illuminated bridges could impact the heterogeneity of a river by night, considering that actual bridges might have much more complex structures with complex sequences of step functions. Also, the model highlights the variability in bridge illumination scenarios, which can serve as a guide to shape future experimental designs examining the effects of bridge illumination on freshwater systems.

Even though there are only few studies that tested the effects of ALAN on migrating fish, still more studies on the impact of ALAN on freshwater is needed to involve decision makers and to create mitigation strategies that protect riverscapes and their biodiversity in an integrated manner with a broad appreciation of the night-time (Hölker et al., 2023).

Limitations of the study

Due to the character of a pilot study, there are some limitations to the presented work. Here, we outline some issues that we would recommend to improve in future studies.

Although we used a tripod and short exposure time following our experience from previous work (Jechow et al., 2017), we recommend the use of a gimbal camera stabilizer to compensate the movement of a moving and rocking boat in future studies.

Furthermore, the number of stops per measurement site was limited by the scheduled closure of the locks during our study. However, with more time at hand we would recommend more stops per bridge, underneath the bridge itself and in open waters nearby the bridge, and ideally also multiple passes. In total, a higher spatial resolution would be desirable and ideally a two-dimensional mapping of the irradiance and radiance distribution. However, this goes with the compromise of the number of bridges that can be quantified per night and the distance that can be covered. For an individual bridge, a high spatial resolution should be the target, which could potentially provide a finer resolution on the exact function of the decrease or increase of light levels.

For future studies it is recommended to also use a wider set of measurement tools, like a continuously measuring illuminance metre, a spectroradiometer to obtain spectral power distribution and potentially multiple cameras to obtain vertical and horizontal plane data in parallel, ideally also obtaining data continuously and potentially under the water surface or from water samplings (see Jechow & Hölker, 2019 for proposed measuring platforms), Additionally, one could obtain more information on the bridge geometry, as well as other characteristics of the bridge illumination, including the type of light source, the distance between luminaires, etc.

Future ALAN research in freshwater ecosystems

Future ALAN research in freshwater ecosystems should involve a wide array of measurements including cameras, sky radiance meters, lux meters, spectrometers and the use of drones above the water surface to develop a finer spatial resolution of the illuminated areas that also consider light planning approaches (the distance between luminaires, the distance between the river bank and the luminaire, if luminaires are shielded, etc.). Also, tools that could measure light even underwater. Such data can be linked with remote sensing data from aerial measurements or satellites (Jechow & Hölker, 2019).

To effectively tackle the existing knowledge gaps within the different disciplines of ALAN, we propose the link between measurement results and a conceptual model. This approach aims to address the missing ecological knowledge on the potential effect of light changes that might alter the behaviour of migratory fish, as it is crucial information for policy-makers and the lighting industry, to understand issues and develop potential solutions to minimize light pollution in a comprehensive manner.

Adhering to the use of illumination sustainably, exclusively in the passage area, remains still an uncommon approach, nonetheless a needed one (Hölker et al., 2023). Still, typically applied lighting systems could be better controlled to avoid light barriers in aquatic habitats by night. However, the current conceptual framework could be a communication tool to sensitize citizens and decision makers on how illuminated bridges affect rivers and aquatic biodiversity.

Conclusion

Our measurements show that bridges can induce varied and different types of unnatural illumination scenarios that may deteriorate or fragment aquatic habitats after dusk. Additionally, the conceptual model presented here demonstrates how typical bridge illumination conditions may induce different behavioural responses in migrating fish and the possible fitness implications for these migratory species.

The results of this study highlight the need for further studies on the impacts of ALAN on freshwater systems, as well as more detailed assessments of light environments in aquatic habitats (Hölker et al., 2023). Given the wide array of disciplines involved in the issue of light pollution, it is imperative to address this with an inter- and transdisciplinary approach (Hölker et al., 2010; Pérez Vega et al., 2022). Better descriptions of ALAN in rivers can support the development of sound transdisciplinary solutions, ideally as an emerging collaboration between practice, research, production, decision-making and planning (Hölker et al., 2021; Pérez Vega et al., 2021; Zielinska-Dabkowska, 2022). Establishing such transdisciplinary approaches can help professionals involved in light planning and design to address the United Nations Sustainable Development Goal (SDG14, 2015) for the integrity of life below water, the assessment of new and existing lighting design, and to facilitate the evaluation of new, existing, and sustainable lighting solutions (Stone et al., 2021; Pérez Vega et al., 2022; Sordello et al., 2022).

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CRediT authorship contribution statement

Catherine Pérez Vega: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Conceptualization, Visualization, Writing – original draft, Writing – review & editing. **Andreas Jechow:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Conceptualization, Visualization, Supervision. **James A. Campbell:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Karolina M. Zielinska-Dabkowska:** Conceptualization, Writing – review & editing, Supervision. **Franz Hölker:** Conceptualization, Writing – original draft, Writing – review & editing, Funding acquisition, Supervision.

Declaration of Competing Interest

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

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.baae.2023.11.001.

References

Aarestrup, K., Økland, F., Hansen, M. M., Righton, D., Gargan, P., Castonguay, M., et al. (2009). Oceanic spawning migration of the European eel (*Anguilla anguilla*). *Science (New York, N.Y.), 325*(5948), 1660. https://doi.org/10.1126/science.1178120

Ali, M. A. (1962). Influence of light intensity on retinal adaptation in Atlantic salmon (*Salmo salar*) yearlings. *Canadian Journal of Zoology, 40*(4), 561–570. https://doi.org/10.1139/z62-049

Antonsson, T., & Gudjonsson, S. (2002). Variability in timing and characteristics of Atlantic salmon smolt in Icelandic rivers. *Transactions of the American Fisheries Society, 131*(4), 643–655. https://doi.org/10.1577/1548-8659(2002)131<3C0643:VITACO>3E2.0.CO;2

Barré, K., Spoelstra, K., Bas, Y., Challéat, S., Kiri Ing, R., Azam, C., … Le Viol, I. (2021). Artificial light may change flight patterns of bats near bridges along urban waterways. *Animal Conservation, 24*(2), 259–267. https://doi.org/10.1111/acv.12635

Burnside, B., Adler, R., & O'connor, P. (1983). Retinomotor pigment migration in the teleost retinal pigment epithelium. *Investigative Ophthalmology & Visual Science, 24*, 1–15.

Cullen, P., & McCarthy, T. (2000). The effects of artificial light on the distribution of catches of silver eel, *Anguilla anguilla* (L.), across the Killaloe eel weir in the Lower River Shannon. *Biology and Environment-Proceedings of The Royal Irish Academy, 100B*, 165–169. https://www.jstor.org/stable/20500095.

Dingle, H., & Drake, V. A. (2007). What is migration? *Bioscience, 57*(2), 113–121. https://doi.org/10.1641/B570206

Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z. I., Knowler, D. J., Lévêque, C., et al. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews, 81*(2), 163–182. https://doi.org/10.1017/S1464793105006950

Durif, C., Elie, P., Gosset, C., Rives, J., & Travade, F. (2000). Behavioral study of downstream migrating eels by radio-telemetry at a small hydroelectric power plant. In D. A. Dixon (Ed.), *Biology, management, and protection of catadromous eels* (pp. 343–356). Bethesda, MD: American Fisheries Society.

Elvidge, C. K., Ford, M. I., Pratt, T. C., Smokorowski, K. E., Sills, M., Patrick, P. H., et al. (2018). Behavioural guidance of yellow-stage American eel *Anguilla rostrata* with a light-emitting diode device. *Endangered Species Research, 35*, 159–168. https://doi.org/10.3354/esr00884

Fischer, J., & Lindemayer, D. B. (2007). Landscape modification and habitat fragmentation: A synthesis. *Global Ecology and Biogeography: A Journal of Macroecology, 16*, 265–280. https://doi.org/10.1111/j.1466-8238.2007.00287.x

Hänel, A., Posch, T., Ribas, S. J., Aubé, M., Duriscoe, D., Jechow, A., … Spoelstra, H. (2018). Measuring night sky brightness: methods and challenges. *Journal of Quantitative Spectroscopy and Radiative Transfer, 205*, 278–290. https://doi.org/10.1016/j.jqsrt.2017.09.008

Hölker, F., Bolliger, J., Davies, T. W., Giavi, S., Jechow, A., Kalinkat, G., et al. (2021). 11 pressing research questions on how light pollution affects biodiversity. *Frontiers in Ecology and Evolution, 9*, Article 767177. https://doi.org/10.3389/fevo.2021.767177

Hölker, F., Jechow, A., Schroer, S., Tockner, K., & Gessner, M. O. (2023). Light pollution of freshwater ecosystems: Principles, ecological impacts and remedies. *Philosophical Transactions of the Royal Society B, 378*, Article 20220360. https://doi.org/10.1098/rstb.2022.0360

Hölker, F., Wolter, C., Perkin, E. K., & Tockner, K. (2010). Light pollution as a biodiversity threat. *Trends in Ecology & Evolution, 25*(12), 681–682. https://doi.org/10.1016/j.tree.2010.09.007

Hadderingh, R. H., Van Aerssen, G. H. F. M., De Beijer, R. F. L. J., & Van Der Velde, G. (1999). Reaction of silver eels to artificial light sources and water currents: An experimental deflection study. *Regulated Rivers Research & Management, 15*(4), 365–371. https://doi.org/10.1068/d01k

Haraldstad, Ø., Vøllestad, L. A., & Jonsson, B. (1985). Descent of European silver eels, Anguilla anguilla L., in a Norwegian watercourse. *Journal of Fish Biology, 26*(1), 37–41. https://doi.org/10.1111/j.1095-8649.1985.tb04238.x

Hasler, A. D. (1956). Perception of pathways by fishes in migration. *Quarterly Review of Biology, 31*(3), 200–209. https://doi.org/10.1086/401394

Jechow, A., & Hölker, F. (2019). How dark is a river? Artificial light at night in aquatic systems and the need for comprehensive night-time light measurements. *Wiley Interdisciplinary Reviews: Water, 6*(6), e1388. https://doi.org/10.1002/wat2.1388

Jechow, A., & Hölker, F. (2020). Evidence that reduced air and road traffic decreased artificial night-time skyglow during COVID-19 lockdown in Berlin, Germany. *Remote Sensing, 12*(20), 3412. https://doi.org/10.3390/rs12203412

Jechow, A., Hölker, F., Kolláth, Z., Gessner, M. O., & Kyba, C. C. (2016). Evaluating the summer night sky brightness at a research field site on Lake Stechlin in northeastern Germany. *Journal of Quantitative Spectroscopy and Radiative Transfer, 181*, 24–32. https://doi.org/10.1016/j.jqsrt.2016.02.005

Jechow, A., Kolláth, Z., Lerner, A., Hänel, A., Shashar, N., Hölker, F., et al. (2017). Measuring light pollution with fisheye lens imagery from a moving boat–a proof of concept. *International Journal of Sustainable Lighting, 19*(1), 15–25. https://doi.org/10.48550/arXiv.1703.08484

Jechow, A., Kyba, C. C. M., & Hölker, F. (2019). Beyond all-sky: Assessing ecological light pollution using multi-spectral full-sphere fisheye lens imaging. *Journal of Imaging, 5* (4), 46. https://doi.org/10.3390/jimaging5040046

Jechow, A., Kyba, C. C. M., & Hölker, F. (2020). Mapping the brightness and color of urban to rural skyglow with all-sky photometry. *Journal of Quantitative Spectroscopy and Radiative Transfer, 250*, Article 106988. https://doi.org/10.1016/j.jqsrt.2020.106988

Johnsen, S. (2012). *The optics of life: A biologist's guide to light in nature*. Princeton University Press.

Kuechly, H. U., Kyba, C. C., Ruhtz, T., Lindemann, C., Wolter, C., Fischer, J., et al. (2012). Aerial survey and spatial analysis of sources of light pollution in Berlin, Germany. *Remote Sensing of Environment, 126*, 39–50. https://doi.org/10.1016/j.rse.2012.08.008

Kurvers, R. H. J. M., & Hölker, F. (2015). Bright nights and social interactions: A neglected issue. *Behavioral Ecology: Official Journal of the International Society for Behavioral Ecology, 26*(2), 334–339. https://doi.org/10.1093/beheco/aru223

Lowe, R. H. (1952). The influence of light and other factors on the seaward migration of the silver eel (*Anguilla anguilla* L.). *The Journal of Animal Ecology, 21*, 275–309. https://doi.org/10.2307/1963

McConnell, A., Routledge, R., & Connors, B. M. (2010). Effect of artificial light on marine invertebrate and fish abundance in an area of salmon farming. *Marine Ecology Progress Series, 419*, 147–156. https://doi.org/10.3354/meps08822

McCormick, S. D., Hansen, L. P., Quinn, T. P., & Saunders, R. L. (1998). Movement, migration, and smolting of Atlantic salmon (*Salmo salar*). *Canadian Journal of Fisheries and Aquatic Sciences, 55*(S1), 77–92. https://doi.org/10.1139/d98-011

Moore, M. V., Pierce, S. M., Walsh, H. M., Kvalvik, S. K., & Lim, J. D. (2000). Urban light pollution alters the diel vertical migration of Daphnia. *Internationale Vereinigung für Theoretische und Angewandte Limnologie: Verhandlungen, 27*(2), 779–782. https://doi.org/10.1080/03680770.1998.11901341

Myers, G. S. (1949). Usage of anadromous, catadromous and allied terms for migratory fishes. *Copeia, 1949*(2), 89–97. https://doi.org/10.2307/1438482

Nützmann, G., Wolter, C., Venohr, M., & Pusch, M. (2011). Historical patterns of anthropogenic impacts on freshwaters in the Berlin-Brandenburg region. *DIE ERDE, 142*(1–2), 41–64. https://www.die-erde.org/index.php/die-erde/article/view/42.

Nankoo, S., Raymond, S., & Galvez-Cloutier, R. (2019). The impact of the Jacques Cartier bridge illumination on the food chain: From insects to predators. *Community Ecology: CE, 20*, 172–180. https://doi.org/10.1556/168.2019.20.2.7

Nelson, T. R., Michel, C. J., Gary, M. P., Lehman, B. M., Demetras, N. J., Hammen, J. J., et al. (2021). Effects of artificial lighting at night on predator density and salmonid predation. *Transactions of the American Fisheries Society, 150*(2), 147–159. https://doi.org/10.1002/tafs.10286

Nightingale, B., Longcore, T., & Simenstad, C.A. (2006). *Artificial night lighting and fishes.* In C., Rich & T., Longcore (Eds.), *Ecological consequences of artificial night lighting*, 11, (pp. 257–276). Island Press.

Ono, K., & Simenstad, C. A. (2014). Reducing the effect of overwater structures on migrating juvenile salmon: An experiment with light. *Ecological Engineering, 71*, 180–189. https://doi.org/10.1016/j.ecoleng.2014.07.010

Pérez Vega, C., Zielinska-Dabkowska, K. M., Schroer, S., Jechow, A., & Hölker, F. (2022). A systematic review for establishing relevant environmental parameters for urban lighting: Translating research into practice. *Sustainability, 14*(3), 1107.

Pérez Vega, C., Zielinska-Dabkowska, K. M.&, & Hölker, F. (2021). Urban lighting research transdisciplinary framework—a collaborative process with lighting professionals. *International Journal of Environmental Research and Public Health, 18*, 642. https://doi.org/10.3390/ijerph18020624

Perkin, E. K., Hölker, F., Heller, S., & Berghahn, R. (2014a). Artificial light and nocturnal activity in gammarids. *PeerJ, 2*, e279. https://doi.org/10.7717/peerj.279

Perkin, E. K., Hölker, F., Tockner, K., & Richardson, J. S. (2014b). Artificial light as a disturbance to light-naïve streams. *Freshwater Biology, 59*(11), 2235–2244. https://doi.org/10.1111/fwb.12426

Rikardsen, A. H., Haugland, M., Bjørn, P. A., Finstad, B., Knudsen, R., Dempson, J. B., et al. (2004). Geographical differences in marine feeding of Atlantic salmon post-smolts in Norwegian fjords. *Journal of Fish Biology, 64*(6), 1655–1679. https://doi.org/10.1111/j.0022-1112.2004.00425.x

Riley, W. D., Bendall, B., Ives, M. J., Edmonds, N. J., & Maxwell, D. L. (2012). Street lighting disrupts the diel migratory pattern of wild Atlantic salmon, *Salmo salar* L., smolts leaving their natal stream. *Aquaculture (Amsterdam, Netherlands), 330*, 74–81. https://doi.org/10.1016/j.aquaculture.2011.12.009

Riley, W. D., Davison, P. I., Maxwell, D. L., Newman, R. C., & Ives, M. J. (2015). A laboratory experiment to determine the dispersal response of Atlantic salmon (*Salmo salar*) fry to street light intensity. *Freshwater Biology, 60*(5), 1016–1028. https://doi.org/10.1111/fwb.12568

Riley, W. D., Davison, P. I., Maxwell, D. L., & Bendall, B. (2013). Street lighting delays and disrupts the dispersal of *Atlantic salmon* (*Salmo salar*) fry. *Biological Conservation, 158*, 140–146. https://doi.org/10.1016/j.biocon.2012.09.022

SDG14. (2015). *Life below water.* Retrieved from https://www.globalgoals.org/goals/14-life-below-water. Accessed March 15, 2023.

Shapovalov, L. (1941). The homing instinct in trout and salmon. In *Proceedings of the 6th science congress, III* (pp. 317–322).

Smith, R. J. F. (2012). *The control of fish migration, 17*. Springer Science & Business Media.

Smyth, T. J., Wright, A. E., Mckee, D., Tidau, S., Tamir, R., Dubinsky, Z., et al. (2021). A global atlas of artificial light at night under the sea. *Elementa: Science of the Anthropocene, 9*(1), 00049. https://doi.org/10.1525/elementa.2021.00049

Sordello, R., Busson, S., Cornuau, J. H., Deverchère, P., Faure, B., Guetté, A., et al. (2022). A plea for a worldwide development of dark infrastructure for biodiversity–practical examples and ways to go forward. *Landscape and Urban Planning, 219*, Article 104332. https://doi.org/10.1016/j.landurbplan.2021.104332

Stein, F., Doering-Arjes, P., Fladung, E., Brämick, U., Bendall, B., & Schröder, B. (2016). Downstream migration of the European eel (Anguilla anguilla) in the Elbe River, Germany: Movement patterns and the potential impact of environmental factors. *River Research and Applications, 32*(4), 666–676. https://doi.org/10.1002/rra.2881

Stone, T., Dijkstra, I., & Danielse, T. (2021). Dark acupuncture: A design strategy for sustainable lighting. *International Journal of Sustainable Lighting, 23*(2), 70–87. https://doi.org/10.26607/ijsl.v23i2.112

Svedäng, H., & Wickström, H. (1997). Low fat contents in female silver eels: Indications of insufficient energetic stores for migration and gonadal development. *Journal of Fish Biology, 50*, 475–486. https://doi.org/10.1111/j.1095-8649.1997.tb01943.x

Szaz, D., Horvath, G., Barta, A., Robertson, B. A., Farkas, A.&, Egri, A., et al. (2015). Lamp-lit bridges as dual light-traps for the night-swarming mayfly, *Ephoron virgo*: Interaction of polarized and unpolarized light pollution. *PLoS One, 10*, Article e0121194. https://doi.org/10.1371/journal.pone.0121194

Tétard, S., Maire, A., Lemaire, M., De Oliveira, E., Martin, P., & Courret, D. (2019). Behaviour of Atlantic salmon smolts approaching a bypass under light and dark conditions: Importance of fish development. *Ecological Engineering, 131*, 39–52. https://doi.org/10.1016/j.ecoleng.2019.02.021

Vøllestad, L. A., Jonsson, B., Hvidsten, N. A., & Næesje, T. F. (1994). Experimental test of environmental factors influencing the seaward migration of European silver eels. *Journal of Fish Biology, 45*(4), 641–651. https://doi.org/10.1111/j.1095-8649.1994.tb00930.x

Van den Thillart, G., Dufour, S., & Rankin, J. C. (2009). Spawning migration of the European eel. In *Fish & fisheries series, 30*. Springer Dordrecht. https://doi.org/10.1007/978-1-4020-9095-0

Vowles, A. S., & Kemp, P. S. (2021). Artificial light at night (ALAN) affects the downstream movement behavior of the critically endangered European eel, *Anguilla anguilla*. *Environmental Pollution (Barking, Essex : 1987), 274*, Article 116585. https://doi.org/10.1016/j.envpol.2021.116585

Zielinska-Dabkowska, K. M. (2013). To light or not to light: Exterior illumination of tall buildings and bridges and its negative impact on the life of birds and fish. What Professional Lighting Designers Need to Know. *Magazine for Professional Lighting Design, November/December*, 38–43. Retrieved from Https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.836.1111&rep=rep1&type=pdf.

Zielinska-Dabkowska, K. M. (2022). Healthier and environmentally responsible sustainable cities and communitiees. A new design framework and planning approach for urban illumination. *Sustainability, 14*, 14525. https://doi.org/10.3390/su142114525