Pathways Towards Responsible Lighting in Norfolk

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Version: Draft

Executive Summary

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1 Introduction

This case study, Responsible Lighting: Pathways Towards Responsible Lighting in Norfolk, examines artificial light at night (ALAN) as a human-controlled environmental hazard embedded within the city's infrastructure. Rather than treating light pollution as an aesthetic issue, this project frames it as a complex, system-level challenge that intersects with ecological health, human well-being, public safety, and urban development. The central goal of this study is to envision a future where lighting in Norfolk is designed intentionally and equitably to maximize safety while minimizing impacts on human health and wildlife. This study applies a transdisciplinary framework to understand ALAN as a wicked problem, defined by competing priorities, uncertainty, and the absence of a single solution (Rittel & Webber, 1973). The issue is shaped by tensions between safety, economic activity, ecological preservation, and social expectations of illuminated spaces. Decisions made within this system have long-term consequences that are difficult to reverse, reinforcing the need for thoughtful and coordinated action. The study identifies key stakeholders operating within Norfolk's lighting system, including city planners, public works departments, utility providers, local universities, environmental organizations, businesses, and residential communities, particularly those in vulnerable or low-income areas. Each stakeholder holds varying levels of influence, resources, and priorities, which collectively shape how lighting is implemented and managed across the city.

2 Decision Space and Role Playing

Understanding the role of stakeholders is essential to explaining why responsible lighting in Norfolk is difficult to achieve. The system is shaped by a wide range of actors, including the City of Norfolk, Dominion Energy, VDOT, private developers, federal installations, community members, and advocacy groups, each with different priorities, responsibilities, and constraints. Because authority is fragmented, no single stakeholder has full control over how lighting is designed or managed, which leads to decisions being made in isolation while their impacts accumulate across the system. This creates coordination challenges, where efforts to reduce light pollution may conflict with concerns about cost, safety, liability, or operational needs. Added difficulties arise from unequal influence among stakeholders. Those most affected by excessive lighting, such as residents in highly illuminated or lower income areas, often have the least ability to influence decisions, while institutions with greater control over infrastructure may prioritize efficiency or visibility over ecological and health outcomes. At the same time, deeply rooted beliefs, such as the assumption that brighter lighting improves safety, can limit support for change. These challenges highlight why stakeholder engagement is critical. Addressing light pollution requires not only technical solutions, but also collaboration, shared understanding, and coordinated action across all groups involved.

3 Wicked Problem and Conceptual Models

The process of building the conceptual models in this study helped clarify how the system operates over time and why light pollution continues to persist. By mapping relationships between the built environment, governance, ecological systems, and societal behavior, the models revealed how reinforcing feedback loops, such as economic growth and infrastructure expansion, continue to drive increases in artificial light at night. At the same time, balancing mechanisms, including regulation, public awareness, and advocacy, were shown to be weaker and slower to respond (Gaston et al., 2013). This modeling process highlights an important insight: the persistence of ALAN is not due to a lack of available solutions, but rather the challenge of implementing coordinated change across multiple, interconnected systems. Even when interventions are technically feasible, they must move through layers of legal constraints, institutional resistance, and limited political capacity, which slows progress and limits large-scale impact.

4 Exposed Assets

Understanding exposed assets is essential to explaining why artificial light at night (ALAN) in Norfolk creates widespread and complex impacts across the system. Unlike traditional environmental hazards that affect assets located in a specific path, ALAN is produced continuously from within the built environment, meaning exposure is embedded across the entire socioecological system. The system includes a wide range of exposed assets, including migratory and nocturnal wildlife, urban ecosystems, human populations, and the night sky itself, all of which depend on natural darkness to function properly. Because light is pervasive and difficult to avoid, many of these assets are continuously exposed, often without the ability to adapt or escape its effects. This creates uneven exposure patterns, where species such as migratory birds, insects, and bats experience disruptions to navigation, feeding, and reproduction, while human communities face impacts to sleep, health, and overall well being. Added complexity arises from the fact that those most affected, including lower income communities and sensitive ecological systems, often have the least capacity to influence lighting decisions. At the same time, the loss of natural darkness as a cultural and environmental resource reduces awareness of the issue, making it more difficult to recognize and address. These conditions highlight that exposure to ALAN is not isolated, but system wide, reinforcing the need for coordinated, intentional approaches to reduce harm and protect both ecological and human systems.

5 Identifying System Fragilities

The fragility analysis further shows that Norfolk's lighting system is vulnerable across governance, ecological, social, and built environment dimensions. Governance fragilities, including the Dillon Rule and fragmented authority, limit the city's ability to implement comprehensive policy changes. Ecologically, species already stressed by habitat loss, pollution, and climate change have limited capacity to adapt to disruptions caused by artificial light (Hölker et al.,

2010a). Social fragilities, such as low public awareness and unequal exposure to light pollution, further weaken the system's ability to respond effectively. In many cases, communities experiencing the highest levels of nighttime light have the least influence over the decisions that shape their environment (Gaston et al., 2013). These overlapping fragilities increase the likelihood that small increases in ALAN will produce disproportionately large and longterm impacts.

6 Current and Future Hazards and Threats

The hazard analysis reinforces that ALAN functions as a chronic and cumulative stressor. Its impacts extend across ecological and human systems, disrupting pollination, migration, trophic interactions, and circadian rhythms (Longcore & Rich, 2004; Gaston et al., 2013). Unlike acute environmental hazards, the effects of ALAN are often gradual and difficult to detect, allowing them to persist without immediate policy response. However, global trends show that artificial lighting continues to expand in both intensity and spatial extent, increasing by approximately 2% per year (Kyba et al., 2017). This suggests that without deliberate intervention, Norfolk is likely to follow a similar trajectory of increasing brightness and ecological degradation.

7 Foresight and Possible Future

The scenario analysis highlights that the future of Norfolk's lighting system is not predetermined but shaped by human decisions. Undesirable futures emerge when current practices continue without coordination, resulting in continued ecological degradation and social inequities. Moderate adaptation may slow these trends, but does not fundamentally alter the system's trajectory. Only the desirable future, characterized by intentional, adaptive, and equitable lighting practices, aligns with the goal of balancing safety, ecological health, and community well-being. This reinforces that achieving a desirable future requires proactive governance and coordinated action across stakeholders.

8 Risk Assessments

Understanding risk is essential to explaining how artificial light at night (ALAN) affects both human and ecological systems in Norfolk. Unlike traditional hazards that occur intermittently, ALAN is a continuous, internally generated stressor embedded in the city's infrastructure, resulting in constant exposure and cumulative impacts over time. Risk within this system is shaped by the interaction between the presence of the hazard, the sensitivity of exposed systems, and the value of what is affected. Highly sensitive systems, such as migratory bird populations, nocturnal wildlife, and human communities, experience greater disruption under persistent light exposure, particularly in a region like Norfolk that lies within the Atlantic Flyway. At the same time, the value of these systems is high, as they provide essential ecological services, support public health, and contribute to overall quality of life. This creates elevated risk in scenarios where light pollution remains unmanaged. However, risk is not one-dimensional. There are also trade offs associated with reducing light, particularly in relation to visibility and safety, where insufficient lighting may increase the likelihood of accidents or other hazards. These competing risks highlight the complexity of decision-making within the system, where both excessive and insufficient lighting carry consequences. Overall, risk in Norfolk's lighting system is not static but evolves based on how lighting is designed, managed, and coordinated across stakeholders, reinforcing the need for intentional and balanced approaches to reduce long term impacts.

9 Transformation Knowledge: Assessing Interventions

Considering interventions is essential to understanding how artificial light at night (ALAN) in Norfolk can be more effectively managed to reduce long-term impacts. Currently, outdoor lighting is treated as an individual commodity, where property owners and institutions control light output without accounting for its broader effects on shared environmental and social systems. This results in cumulative impacts that extend beyond property boundaries, affecting ecosystems, human health, and the night sky as a common resource. Addressing this challenge requires a shift in perspective, recognizing darkness as a form of infrastructure that must be intentionally managed and protected. Effective interventions therefore focus on establishing coordinated governance, improving lighting design, and reducing unnecessary light at the source, while balancing the functional benefits that lighting provides for safety and activity. However, these efforts are shaped by real-world constraints, including existing infrastructure, regulatory limitations, and conflicting incentives, particularly within utility and development systems. As a result, meaningful change depends not only on technical solutions, but also on aligning policies, institutions, and stakeholder actions over time. Overall, this section highlights that reducing ALAN impacts in Norfolk will require a coordinated, system-level approach that integrates governance, design, and community engagement to move toward a more sustainable and balanced nighttime environment.

10 Discussion and Conclusion

The case study shows that ALAN shapes the complex socioecological systems in Norfolk, making responsible management a challenge. Regulation and implementation is diffused across multiple authorities with different priorities, and influenced by social norms. Evidence is clear that ALAN has severe ecological impacts that span the entire system. The study was limited by a lack of large-scale data localized to the City of Norfolk. Furthermore, the authors could not engage directly with all stakeholders, limiting the understanding of stakeholder perspectives to roleplaying exercises and analysis of literature. Future studies are needed to further understand the direct impacts of ALAN specific to Norfolk and its stakeholders.

In conclusion, the future of responsible lighting in Norfolk is reliant on how decisions are made across the system. Undesirable futures are the result of the continuation of current regime and neglect of evidence based recommendation. Achieving a desirable future will require intentional and coordinated actions across all actors. Moving forward, artificial lighting needs to be recognized as something that should be managed and treated with caution, not something that society is automatically entitled to.

11 Recommendations

Recognizing that the night is a shared commons and is not yet treated with deliberate care... Realizing that without coordinated care, regional light pollution will increase... Acknowledging that there are regulations that impede and contradict necessary interventions for managing ALAN responsibly... And emphasizing that effective solutions to the problems created by ALAN are sequenced by efficacy rather than ease... We declare the need that the Virginia General Assembly authorize Virginia municipalities to regulate ALAN beyond what state law currently allows, the State Corporation Commission allow Norfolk to reduce streetlight count and output, and that there is cooperation across all

agencies in Hampton Roads to pursue responsible lighting.

We recommend that Citizens for Responsible Lighting:

1. **Sustain and expand advocacy.**
2. Advocate for the city to **recognize light as a pollutant.**
3. Advocate for an **adaptive spectrum and retrofit of outdoor fixtures, to be funded by a corporate light-pollution levy.**
4. Advocate that the city **codify *Lights Out Hampton Roads* with bird migration-response dimming.**
5. Advocate for **strategic de-illumination.**

1 Introduction

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Artificial lighting has become an essential part of modern urban life, supporting public safety, economic activity, transportation, and recreation. Rapid expansion of outdoor lighting in cities has also created an unintended environmental challenge known as light pollution. Although nighttime skyglow was first noted as an astronomical concern in the early twentieth century, the ecological and human health consequences of artificial light at night (ALAN) were not formally recognized by the scientific community until the 1990s and 2000s, when foundational research began documenting disruption to circadian biology, species behavior, and ecosystem function (Hölker et al. 2010a; Longcore and Rich 2004). In Norfolk, Virginia, increasing levels of artificial light from streets, commercial areas, residential neighborhoods, sports complexes, and airport infrastructure contribute to excessive nighttime illumination. This growing brightness alters natural darkness cycles, affecting both human communities and surrounding ecosystems. Light pollution has been shown to disrupt wildlife behavior, particularly for migratory birds, nocturnal species, and coastal organisms that rely on natural light cues for navigation, feeding, and reproduction (Longcore and Rich 2004; Hölker et al. 2010b; Manfrin et al. 2017). Beyond its ecological effects, ALAN poses significant risks to human health, including disruption of circadian rhythms, impaired sleep quality, and associations with increased rates of cancer and metabolic disorders (Wang et al. 2023). At the same time, poorly designed lighting systems can create unnecessary skyglow, energy waste, and light trespass into nearby homes and habitats.

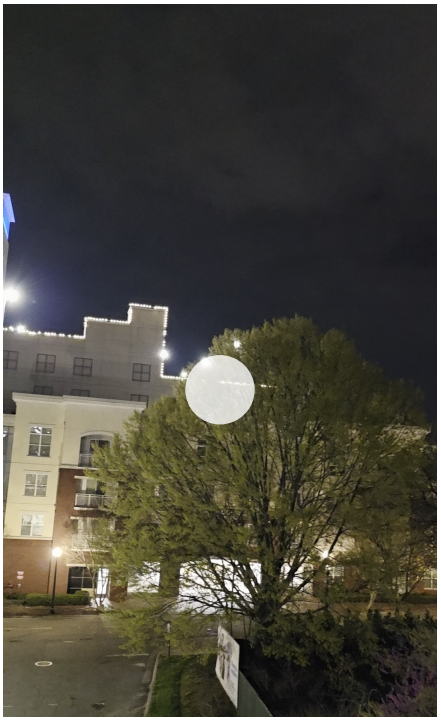
For most of human history, darkness was part of the daily rhythm of life. It shaped how people moved, worked, and rested. The night sky informed navigation, agriculture, spiritual practice, storytelling, and early scientific observation across cultures. The shifting patterns of the stars across the night sky helped structure calendars and guide travel, giving people a way to understand where they were and how they belonged in the world. Watching meteor showers, catching fireflies at dusk, or falling asleep under a sky dense with stars were ordinary experiences rather than rare events. For many people living in urbanized areas today, those experiences are no longer accessible. Kyba et al. (2017) show that Earth's artificially lit outdoor area increased by roughly 2% per year in both lit extent and brightness over the first half of the 2010s. While the change has been gradual on a yearly scale, it has continued to accumulate. Across generations, the night sky children inherit has become unrecognizable as the same one their grandparents knew.

The spread of artificial lighting outpaced scientific understanding, and the problem was only gradually framed as an ecological and public-health issue. Astronomers were the first professional community to organize around the problem, founding the International Dark-Sky Association (now DarkSky International) in 1988 to advocate for the preservation of natural darkness, initially to protect the quality of astronomical observations. As more evidence emerged, scientists and advocates began to worry about a much broader set of impacts. Longcore and Rich (2004) introduced the concept of ecological light pollution, documenting how artificial light at night alters behavior, physiology, and survival across a wide range of species. Hölker et al. (2010a) pushed the conversation further, describing artificial light at night as a global stressor and calling for a transdisciplinary research agenda that treats light pollution as a problem spanning ecology, public health, engineering, governance, and culture. By the time Gaston et al. (2013) published their mechanistic review of the ecological impacts of nighttime light, artificial light at night was widely understood as a persistent, chronic pollutant, with effects that ripple through ecological and social systems and often become visible only after years of exposure.

What remains less visible is the loss that does not show up easily in conventional data. The cultural and experiential dimensions of darkness are harder to measure, which makes them easier to overlook in policy and planning. On April 1, 2026, NASA launched Artemis II, sending four astronauts on the first crewed lunar-orbit mission since the Apollo program and setting a new record for the farthest distance humans have traveled from Earth (NASA 2026). The mission reflects a renewed investment in exploration and in humanity's relationship with the wider universe. At the same time, most children growing up in cities such as Norfolk cannot see the stars surrounding the Moon from their own streets. The chasm between what we attempt in space and what we tolerate in our own skies is embedded in the ways lighting is governed, funded, and normalized, and it is part of the same system this case study seeks to understand.

1.1 Urban Light Pollution and Its Impacts in Norfolk

This case study supports the work of Citizens for Responsible Lighting (CRL), a non-governmental organization in Norfolk that advocates for lighting practices that meet societal needs while reducing ecological and community impacts. The challenges being addressed are how to design and manage urban lighting systems that maintain safety and the local economy while protecting biodiversity and reducing environmental harm. The issue occurs across multiple interconnected systems, including the urban ecosystem of Norfolk, nearby coastal and estuarine habitats connected to the Chesapeake Bay watershed, and the human communities that live, work, and play within the city. Both human and non-human actors are affected. Residents may experience sleep disruption, glare, and reduced night sky visibility, while wildlife such as migratory birds, bats, insects, and other nocturnal species experience disorientation, habitat alteration, and increased mortality due to excessive artificial lighting at night (ALAN) (Longcore and Rich 2004; Gaston et al. 2015).



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Video 1: In the video, American robins (Turdus migratorius) can be heard singing in downtown Norfolk at 2:00am.

Video 1 shows American robins (*Turdus migratorius*) singing in downtown Norfolk at around 2:00 AM. Under normal conditions, robins are active during the day and quiet at night. Hearing them sing at this hour is not typical. Artificial light at night has been shown to disrupt sleep cycles in birds, reduce REM sleep, and interfere with song learning, which plays a role in attracting mates and holding territory (Aulsebrook et al. 2021). It can also shift activity into nighttime hours, pushing birds to forage when they would normally be resting. The behavior captured here offers a glimpse of how Norfolk's nighttime light environment is already changing the rhythms of common, familiar species.

1.2 Drivers of Artificial Light at Night

The cause of the problem is complex and distributed among many societal agents. Urban development, expanding transportation infrastructure, commercial growth, and evolving public expectations for nighttime visibility have all contributed to increased ALAN. Multiple stakeholders influence how lighting systems are designed and used, including city planning departments, public works agencies, airport authorities, sports facilities, businesses, residential communities, and educational institutions such as Old Dominion University and Norfolk State University. At the same time, organizations like Citizens for Responsible Lighting, environmental groups, and research institutions are working to raise awareness and develop solutions that balance safety, economic activity, and environmental stewardship. Responsible lighting represents a wicked problem because it involves competing priorities, uncertain ecological impacts, and decisions that interject into institutional and disciplinary boundaries (Rittel and Webber 1973; Kolko 2012). Stakeholders often share common goals, such as public safety and economic vitality, but may disagree on how lighting should be designed, regulated, or funded. Solutions require coordination between government agencies, businesses, community members, and environmental advocates. Efforts to address the issue already include the adoption of energy-efficient LED technology, updated lighting ordinances, and growing public awareness of light pollution impacts. Without coordinated planning, technology upgrades alone can sometimes increase overall brightness rather than reduce it (Kyba et al. 2017).

1.3 Advancing Towards Responsible Lighting in Norfolk

This case study aims to support stakeholders in Norfolk by examining responsible lighting as a socioecological system and identifying pathways toward a desirable future. To do so, the study employs the MARI Case Study Template (MCST), a transdisciplinary, participatory methodology that integrates systems thinking, stakeholder mapping, and conceptual modeling to analyze wicked problems in the context of mitigation and adaptation science (Plag 2024). The case study combines scientific evidence with local stakeholder knowledge to develop a conceptual model of Norfolk's outdoor lighting system, examine system fragilities and hazards, and assess interventions that could move the system toward more desirable trajectories. The report will contribute insights for decision-makers, including city planning and public works departments, airport and sports facility managers, local businesses, schools and universities, and community organizations. By exploring stakeholder perspectives, ecological impacts, and potential interventions, the study seeks to help guide Norfolk toward lighting practices that maintain safety and functionality while protecting biodiversity, reducing environmental impacts, and preserving the natural night environment for future generations.

Figure 7 shows the difference in artificial light exposure between a dense urban area and a lower intensity residential setting, both within Norfolk, VA. In the downtown Norfolk images, lighting is still widespread and very noticeable even late at night, creating visible skyglow and extending beyond where the light is actually needed. This reflects a higher hazard probability and constant exposure within the urban system. In contrast, the residential area shows less intense lighting and darker sky conditions. The visibility of stars suggests lower levels of light pollution, which points to lower hazard probability and reduced exposure, even within the same city. Together, these images highlight how lighting is

not evenly distributed across space. Instead, it varies based on land use, infrastructure, and how lighting is managed. These differences directly influence how much risk different areas experience.



Figure 7: The top images show Granby Street in downtown Norfolk at approximately 1:30 am, where high intensity and continuous artificial lighting create visible skyglow and illumination across the urban corridor. The bottom images show a residential neighborhood a few miles away from downtown Suffolk at approximately 11:00 pm, where lighting is more limited, allowing for darker skies and greater visibility of stars. This comparison highlights the spatial variation in artificial light at night (ALAN) and demonstrates how urban infrastructure contributes to increased light pollution.

The impacts of artificial light at night are not evenly distributed across Norfolk. Residents in denser, lower-income neighborhoods are more likely to experience elevated nighttime light levels due to concentrated street lighting and nearby commercial activity. At the same time, these communities often have fewer resources to reduce exposure and less influence over the lighting decisions that affect their surroundings. This imbalance means that those most affected by light pollution are often the least positioned to advocate for change, a dynamic explored further in the fragility and risk analyses that follow.

1.4 Methodology

Responsible Lighting: Pathways Towards Responsible Lighting in Norfolk frames artificial light at night (ALAN) as a wicked problem, where human safety, economic activity, ecological integrity, and quality of life intersect in complex and often competing ways. Rather than being solely a technical or aesthetic concern, the challenge lies in identifying and navigating a shared pathway toward a desirable future, one in which lighting systems meet human needs while minimizing harm to ecological processes and the night environment.This case study applies a transdisciplinary, participatory modeling approach based on the MARI Case Study Template (MCST) (Plag, 2024). Unlike traditional science and engineering approaches commonly used in the United States, which often focus on isolated variables and technical solutions, participatory modeling emphasizes collaboration, systems thinking, and shared understanding among stakeholders. It is specifically designed to address complex, “wicked” problems that cannot be solved through a single discipline or perspective. A central feature of this methodology is that it does not begin with a fixed problem definition or predetermined solution. Instead, the process starts by bringing together relevant stakeholders to build consensus on what the problem is and to develop a shared understanding of what a desirable future would look like. The outcome of this initial step is the creation of a goal statement that reflects collective values and priorities. This goal then guides all subsequent analysis and decision making.

The methodology follows a structured, stepwise process:

Step 1: Decision Space and Role Playing (Section 2)

Stakeholders are identified and engaged to develop a shared understanding of the problem and to define a desirable future. This step focuses on building consensus and aligning perspectives across different groups.

Step 2: System Understanding (Sections 3-6)

system is analyzed using a socioecological lens to understand how different components interact. This includes:

- Identifying key system elements and relationships (Section 3)
- Assessing system assets and strengths (Section 4)
- Evaluating system fragilities and vulnerabilities (Section 5)
- Identifying internal (endogenic) and external (exogenic) hazards affecting the system (Section 6)
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Step 3: Exploring Possible Futures (Section 7)

A range of plausible future scenarios is developed to explore how the system may evolve under different conditions. These scenarios help illustrate potential trajectories and trade-offs.

Step 4: Risk Assessment (Section 8)

A risk-based framework is applied to evaluate the likelihood and consequences of different futures. This helps identify which outcomes should be avoided and which should be pursued.

Step 5: Identifying Interventions and Pathways (Section 9)

Based on the risk assessment, potential interventions are explored to guide the system toward more desirable futures. These interventions consider feasibility, effectiveness, and stakeholder alignment.

Step 6: Recommendations for Action

The final step translates findings into actionable recommendations for decision-makers, providing guidance on strategies that can support long-term system improvement.

By following this process, participatory modeling provides a clear pathway for navigating complex systems, guiding the reader through how shared understanding is built, risks are evaluated, and meaningful solutions are developed. It invites the reader into the case study not just to observe the problem, but to understand how pathways toward a more desirable future can be intentionally designed.

2 Decision Space and Role Playing

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Responsible lighting in Norfolk does not belong to any single agency, institution, or community group. Instead, it emerges from a crowded and fragmented decision space distributed across municipal government, a regulated utility, federal and state agencies with limited local jurisdiction, private developers, educational institutions, private homeowners and renters, and grassroots advocates who hold formal authority over nothing but influence over everything.

Each actor controls a part of the lighting landscape; no actor controls enough of it to act comprehensively, and no one bears full accountability for the cumulative light environment these decisions produce. At street level, this fragmentation appears as inconsistent fixture types, uneven brightness, and lighting that reflects overlapping decisions rather than a unified plan.

Understanding who holds power over lighting decisions, who absorbs the consequences, and where meaningful leverage for change exists is the starting point for any realistic pathway toward responsible lighting (Rittel and Webber 1973; Plag 2024). These relationships are interpreted on a combimed map in Figure 1, which shows stakeholders by authority and interest, and rules and regulations by relevance and leverage.

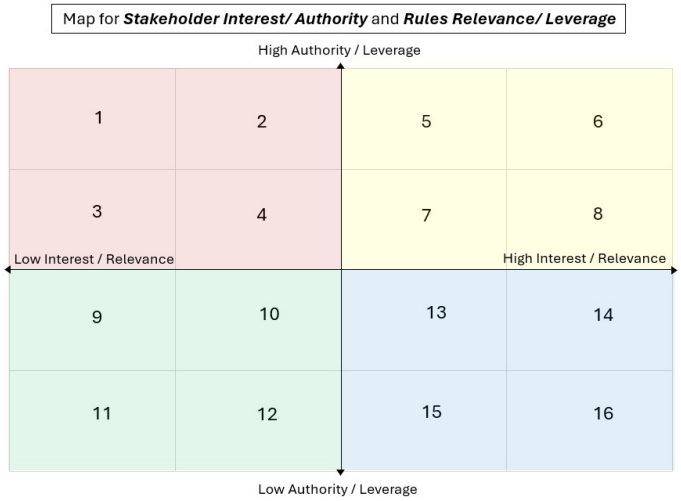

Figure 1: The combined *Stakeholder Interest and Authority* and *Rules Relevance and Leverage* map is divided in to four quadrants, with sections in each quadrant to visualize the interest and authority of different stskeholders regarding the issue of light pollution, and the relevance and leverage of different rules regarding its governance. Table 1 lists the map location of the stakeholders that correlate with the section numbers. Table 2 lists the map location of the rules that correlate with the section numbers.

2.1 Actors and Authority

The stakeholders involved in Norfolk's outdoor lighting system span three broad categories: governance actors with formal regulatory or financial power, social actors who live and work within the built environment shaped by that power, and environmental actors who advocate for ecological and community health (Table 1). Their positions and constraints are not uniform, and mapping them clarifies where change is feasible and where structural barriers are most entrenched.

The City of Norfolk is the central governance actor. It sets zoning and exterior lighting standards for development, coordinates public street lighting through Dominion Energy under a State Corporation Commission–approved street lighting tariff (Virginia Electric and Power Company 2024), and controls the capital budget for infrastructure. Norfolk also holds responsibility for public health, which could provide a legal basis for addressing outdoor lighting where it demonstrably harms human well-being. At the same time, the city operates under the Dillon Rule, a legal doctrine that limits Virginia municipalities to only those powers expressly granted by the state legislature (Va. Code §15.2-2280). Norfolk cannot regulate military property, extend mandates beyond state authorization, or easily renegotiate the terms of its street lighting contracts without a full SCC rate case. Real authority over lighting infrastructure exists, but it is procedurally constrained, departmentally fragmented, and routinely shaped by cost, liability, and political pressures that often override ecological or public health concerns.

Dominion Energy occupies a structurally powerful position. As the energy provider and street-lighting operator, its decisions about fixture type, light output, and contract terms shape what is physically possible on Norfolk's streets. Long-term maintenance contracts and cost recovery requirements mean that upgrades or replacements must clear financial and regulatory hurdles before proceeding. Dominion's institutional incentives prioritize reliability and predictable costs; ecological sensitivity and community health typically enter the calculus only when external pressure places them on the agenda.

The Virginia Department of Transportation (VDOT) sets roadway lighting safety standards that govern a significant portion of public lighting. These standards are risk-averse and liability-driven, rooted in the premise that brighter lighting is safer, which can conflict directly with responsible lighting principles (Virginia Department of Transportation 2005; City of Virginia Beach Department of Public Works 2020). Military installations in Norfolk, including Naval Station Norfolk and the Norfolk Naval Shipyard, operate under federal authority and are effectively exempt from city ordinance, creating governance gaps in some of the most intensely lit corridors in the region (Va. Code §15.2-2280).

Among civil society actors, Citizens for Responsible Lighting (CRL) is the most directly engaged. CRL holds no formal decision-making authority but functions as a coalition builder, public educator, and agenda-setter, translating scientific and ecological knowledge into policy pressure (Citizens for Responsible Lighting 2024). Universities, particularly Old Dominion University and Norfolk State University, manage large campuses with substantial lighting footprints and can pilot responsible lighting practices on their own property.

Private homeowners and renters shape the light environment through porch lights, floodlights, decorative and seasonal installations, and indoor lighting visible from the street. Homeowners can modify their own fixtures; renters generally cannot, meaning their exposure to poorly designed lighting is determined by landlord and property-management decisions they have limited leverage to change. Residents and civic leagues experience the direct impacts of lighting—glare, light trespass into homes, sleep disruption, and reduced night sky visibility (Hölker et al. 2010a; Gaston et al. 2013)—but hold limited formal authority beyond their own property lines.

The distribution of lighting infrastructure across Norfolk's neighborhoods is uneven in ways that track socioeconomic geography. Denser, lower-income neighborhoods tend to have higher ambient streetlight levels, more commercial signage, and less tree canopy to buffer light intrusion. These communities bear a greater exposure burden while holding less influence over the planning and procurement decisions that create it (Gaston et al. 2013). This asymmetry compounding every other governance fragility in the system means that the people most affected by overlighting are often those least positioned to change it.

Table 1: The Stakeholder table outlines the relevant stakeholders and theri role, primary needs, constraints, and their position on light pollution in Norfolk, VA. Map Loaction refers to the location of the rule on the map in Figure 1.

Stakeholder	Role	Primary Need	Key Constraint	Likely Position	Map Location
City Government	Sets rules & budgets	Keep people safe and avoid backlash	Limited budgets; legal liability; public perception	*Cautiously supportive if risks & costs are low*	5
Dominion Energy	Provides & maintains lighting	Reliable, low-risk operations	Long-term contracts	*Open if costs and contracts aren't disr upted*	6
VDOT	Sets road standards	Prevent crashes and liability	Safety design requirements	*Risk-averse; safety = top priority*	13
Residents & Civic Leagues	Live with the impacts	Safe neighborhoods without glare	Little formal authority	*Split—depends on safety perception & education*	16
USFWS	Protects species	Prevent harm to wildlife	Limited jurisdiction	*Supportive where authority applies*	8
Army Corps of Engineers	Permits major projects	Stay within permit scope	Narrow regulatory mandate	*Neutral unless permits are triggered*	7
EMS / Police	Respond to emergencies	Fast response and visibility	Operational risk	*Concerned about reduced visibility*	14
Universities	Manage large campuses	Safe, usable campuses	Cost and maintenance	*Open to pilots on their own property*	13
NGOs	Push for change	Advance goals	No decision authority	*Actively supportive; agenda-setting*	14
Tourism Interests	Attract visitors	Visibility and nighttime activity	Public perception	*Concerned about limits on visibility*	3
Large Corporations	Manage private sites	Brand image and cost control	Return on investment	*Interested if it's good for image or savings; Bottom-dollar*	6
Transportation Hubs	Run airports / other transit	Safe nighttime operations	Federal rules	*Highly cautious; compliance-driven*	7
Sports Complexes	Use very bright lights at night	Safe, successful events	Safety standards; sunk costs	*Resistant unless event safety & profit are guaranteed*	8
Astronomers	Recreation & education	Preserve dark skies	Limited leverage	*Strongly supportive but indirect*	14

2.2 Rules, Constraints, and Governance Fragmentation

The rules shaping Norfolk's outdoor lighting landscape operate across multiple scales and categories, mapped by relevance and leverage in Table 2. Local zoning and outdoor lighting ordinances, municipal sign regulations, VDOT roadway safety standards, and military/DoD lighting regulations are highly relevant and high-leverage because they directly determine what gets installed and how it operates. Federal laws such as the Migratory Bird Treaty Act and the Endangered Species Act have medium–high relevance to light pollution impacts on wildlife (Longcore and Rich 2004), but their leverage over urban lighting practices is limited by jurisdictional scope: they apply to federal land and federally protected species, not to the full built environment.

Beyond formal rules, unwritten norms and assumptions shape lighting decisions in significant ways. The most influential is the idea that "brighter equals safer." This belief is embedded in public safety practice, engineering standards, and legal liability frameworks, and it functions as a default: those arguing for reduced or redesigned lighting must overcome more scrutiny than those arguing for additional lighting. The paradigm appears in road design manuals, procurement specifications, and tort-liability analyses, and challenging it requires engaging engineering orthodoxy, legal precedent, and widely held public intuitions about safety, all at the same time.

The gendered dimension of this paradigm warrants explicit attention. Claims that "more light makes women safer" are invoked frequently in public-safety discourse, yet the relationship between illumination levels and actual reductions in violence is far less clear than such rhetoric suggests. Brighter lighting can increase visibility for potential victims and potential perpetrators, and it can create a false sense of security that diverts attention from structural conditions—such as housing stability, community presence, and responsive public services—that more directly shape safety. In many cases, the safety discourse around lighting performs protection rather than delivering it, and the communities where overlighting is most aggressive are often the same communities where other forms of public investment have been limited.

Upgrade cost avoidance and the procurement logic of lowest-bid contracting further entrench existing infrastructure. When lighting decisions are driven primarily by cost minimization, fixtures are selected for price and operational

simplicity rather than directionality, spectral quality, or ecological impact. Low public awareness constrains the political will needed to move governing bodies toward action (Kyba et al. 2017). These paradigm-level constraints are not codified as law, but they shape decisions as strongly as many formal ordinances.

This governance landscape exhibits the hallmarks of a wicked problem (Rittel and Webber 1973). Authority is distributed, mandates conflict, and no actor controls enough of the system to act unilaterally. Each stakeholder operates within a legitimate mandate, and those mandates do not align. The fragmentation is structurally predictable, and it is precisely what makes light pollution resistant to straightforward regulatory solutions (Kolko 2012).

Table 2: The Rules table lists the rules that shape ALAN and their relevance and leverage over its governance. Map Loaction refers to the location of the rule on the map in Figure 2.

Rule	Relevance	Leverage	Map Location
Local zoning & outdoor lighting ordinances	High	High	6
Municipal sign regulations (billboards)	Med-high	High	6
Park & public-space lighting policies	Med-high	Med	8
Planning & design review requirements	Med	Med	4
VDOT roadway lighting safety standards	High	High	8
Virginia Coastal Resilience Plan	Low	Low	13
Virginia wildlife conservation guidance	Low-med	Low	16
NEPA Federal environmental review	Low	High	1
Migratory Bird Treaty Act (MBTA)	Med-high	High	8
Endangered Species Act (ESA)	Med-high	High	8
Military/DoD lighting regulations	High	High	5
Lowest bidder/cost (public contracts/procurement)	High	High	6
Energy pricing & efficiency rebates	Med	Med	5
Current lighting infrastructure	Med-high	Med	6
Tourism/commercial/business visibility concerns	Med	Med	4
Upgrade costs & avoidance	Med-high	Med	5
"Brighter = safer" safety paradigm	High	Med	7
Expectation of lighting – streets/spaces (paradigm)	Med-high	Low	16
Aesthetic preferences	Low-med	Low	12
Low public awareness	Low-med	Low	10
Protecting wildlife and ecosystems	High	Low	16
Environmental justice (local communities)	Med	Med/Low	16
Current & future generational impacts	Low	Low	16
Stewardship of the night sky (as a shared resource)	Low	Low	15
Safety-first mentality for decision-making	High	High	7
Fragmented responsibility/governance	Med-high	Med	7
Default for engineering standards > ecology	High	Med	7
Risk aversion & fear of liability	High	High	6

Color Key	State Laws	Economic Rules	Ethical Norms
Local Laws	Federal Laws	Social Norms	Hybrid Rules

2.3 Role Playing and Shared Goal Formation

To surface the diverse interests at stake and test where common ground was achievable, the group conducted a role-playing exercise in which the perspectives of major stakeholder categories were explored and articulated. Participants represented governance actors, social community groups, and environmental organizations, each working from the core question: What is the desired future for outdoor lighting in Norfolk?

Table 7: This table shows how different stakeholders in Norfolk are connected through their shared experiences with nighttime lighting. Residents, schools, public agencies, and community groups all interact with lighting in different ways, but they share common goals of safety, comfort, and environmental care. By mapping these perspectives and desired outcomes, the diagram emphasizes the importance of collaboration and community input in creating responsible lighting systems. This shared vision helps guide Norfolk toward healthier neighborhoods and more sustainable nighttime environments.

Stakeholders	Desirable Future
Social	
Public schools	A future where outdoor lighting keeps students, staff, and families safe during evening activities without disrupting nearby neighborhoods.
Universities	A future where lighting supports late night studying and campus life that helps supports students mental health by protecting students sleep cycles.
Low-income Communities	A future where lighting keeps families safe without disrupting their sleep, health, or peace of mind.
Established Communities	A future with balanced lighting that supports safety, beauty, and environmental quality.
Norfolk International Airport	A future that balances aviation safety and also incorporates environmental responsibility.
Sport Complexes	A future that creates a welcoming, community-centered space that supports recreation without disrupting nearby neighborhoods.
Environmental	
U.S. Fish and Wildlife Service	A future where Norfolk has a more natural lighting environment that protects migratory birds, and benefits people and other wildlife.
Astronomers	A future where Norfolk has dark sky friendly outdoor lighting and a visible night sky that benefits current and future generations of astronomers for personal, educational, and scientific enrichment.
Non-governmental Organizations	A future where Norfolk has a visible night sky that provides safe passage for migratory species, enhances fitness for non-migratory wildlife, and improves overall wellness of people.
Governance	
City of Norfolk (Local Government)	A Norfolk where public infrastructure investments — including street lighting — advance the city's climate resilience commitments, equity priorities, public safety standards, and fiscal responsibility. Lighting decisions are made proactively through evidence-based planning and risk management processes, reducing exposure to liability and avoiding crisis-driven decision-making.
Dominion Energy	A future where lighting efficiency improvements move through normal replacement cycles, cost recovery is secured before work begins, and Dominion is recognized as a sustainability partner — without that recognition becoming leverage for the next mandate.
Military	A future where security requirements are met, energy consumption in non-critical zones is reduced in line with DoD resilience mandates, and off-site light spill is minimized through better fixture design — without the host city ever having grounds to claim jurisdiction over federal property.

Governance actors highlighted the structural tensions most clearly. The City of Norfolk seeks a future in which lighting investments advance climate-resilience commitments, equity priorities, and public-safety standards simultaneously, yet in practice, safety and cost pressures often dominate when those values conflict. Dominion Energy favors a future in which efficiency improvements proceed through normal replacement cycles without disrupting existing cost-recovery arrangements. The military's position centers on meeting security requirements and reducing energy use in non-critical zones while minimizing off-site light spill, without ceding jurisdiction to the host city.

Social stakeholders described futures that were remarkably convergent despite differences in context. Public schools want lighting that keeps students and families safe during evening activities without creating glare or light trespass into surrounding neighborhoods. Universities envision smart, warm-toned, adaptive campus lighting that supports student sleep cycles and demonstrates institutional commitment to environmental responsibility (Hölker et al. 2010b). Low-income communities want streetlights that feel safe without disrupting sleep, health, or peace of mind, and they want a meaningful voice in decisions that shape their streets. Established residential communities seek balanced lighting that supports safety, neighborhood character, and environmental quality. Sports complexes and the airport emphasize safety and operational continuity, while recognizing that shielded, efficient fixtures can reduce off-site impacts without undermining function.

Environmental stakeholders—including CRL, the Audubon Society, Elizabeth River Project, Tidewater Master Naturalists, and Friends of Norfolk's Environment—describe a future in which Norfolk has a visible night sky that provides safe passage for migratory species, supports non-migratory wildlife fitness, and improves overall human wellness (Longcore and Rich 2004; Gaston et al. 2013). The U.S. Fish and Wildlife Service emphasizes a more natural lighting environment that protects migratory birds. Astronomers call for dark-sky-friendly outdoor lighting that preserves the night sky for current and future generations. Under current conditions, much of Norfolk's urban core lies near the upper end of the Bortle dark-sky scale, a nine-point index of sky brightness in which higher values indicate greater artificial sky glow (Bortle 2001), underscoring the extent of night-sky loss.

Across these positions, a common set of values emerged: safety, ecological health, community well-being, and the expectation that light should serve a clear purpose rather than be deployed by default. No stakeholder group identifies light pollution itself as a desired outcome. The divisions arise instead from the institutional weight of existing infrastructure, liability frameworks, procurement constraints, and competing interpretations of what safety requires. Making these tensions explicit is a precondition for any realistic intervention strategy (Rittel and Webber 1973).

The shared goal statement that emerged from this process is:

A future where the artificial light in Norfolk is designed in an intentional and equitable way to minimize impacts on health and wildlife.

This goal treats the night environment as a shared commons—something collectively experienced and collectively shaped—that requires coordination, accountability, and deliberate design rather than incremental expansion without oversight. It does not call for eliminating outdoor lighting; it calls for governing light with the same intentionality that cities apply to air quality, water management, and land use, recognizing that unmanaged light imposes costs that fall disproportionately on those with the least power to influence the decisions that produce it.

3 Wicked Problem and Conceptual Models

Abby Lahey, Danielle Delp

Light pollution in Norfolk operates within a socio-ecological system where infrastructure decisions, governance authority, commercial interests, and ecological processes interact in ways that resist straightforward correction. Artificial light at night (ALAN) accumulates as a stock — not through a single source or decision, but through the aggregate output of streetlights, commercial signage, sports facilities, universities, residences, and military installations, each governed under different rules by different actors with different incentives (Hölker et al. 2010a). The drivers of ALAN are diffuse, the harms are cumulative and often invisible to those causing them, and the authority to act is fragmented across institutions that were never designed to coordinate on this issue.

The shared goal established in Section 2 — a future where Norfolk's artificial light is designed with intention and equity to maximize safety while minimizing impacts on health and wildlife — requires understanding this system well enough to identify where interventions can redirect its trajectory.

These characteristics mark light pollution as a wicked problem in the sense described by Rittel and Webber (1973): the problem resists definitive formulation, has no single correct solution, and forces decision-makers to act under uncertainty and conflicting values. Norfolk's case carries additional features of a super-wicked problem (Levin et al. 2012). Time is running out — ecological harm to migratory birds, pollinators, and coastal organisms is accumulating as ALAN expands globally at a rate of roughly 2% per year in radiance and extent (Kyba et al. 2017), and population-level effects compound over time in ways that are difficult to reverse. There is no central authority: the City of Norfolk, Dominion Energy, VDOT, federal military installations, and private landowners all control different portions of the lighting landscape without any single entity holding comprehensive jurisdiction. Those seeking to solve the problem are also causing it — CRL members, university researchers, and city planners all live and work in buildings that contribute to skyglow. Policies discount the future irrationally: upgrade cost avoidance, lowest-bidder procurement, and the liability logic embedded in the 'brighter equals safer' paradigm all systematically prioritize near-term institutional convenience over long-term ecological and public health outcomes (Longcore and Rich 2004; Gaston et al. 2013).

Understanding why this system behaves the way it does requires identifying the stocks that accumulate or deplete slowly, the flows that drive change, the feedback loops that either reinforce the current trajectory or could redirect it, and the agents whose decisions shape those flows.

Four conceptual models were developed to capture this system at different scales and levels of detail, functioning as a nested set. The Overview Model (Figure 3) traces the broad causal structure connecting the built environment, ecological systems, societal dynamics, and decision-making to light pollution. The Decision Space Model (Figure 4) zooms into the governance and advocacy architecture through which interventions must pass. Two subsystem models provide additional detail: the Built Environment Model (Figure 5) maps the specific pathways by which energy becomes light pollution across Norfolk's infrastructure, and the Ecological Model (Figure 6) traces how light pollution propagates through terrestrial, riparian, coastal, and human systems. Together, these four models provide the systems-level foundation for the fragility, hazard, and foresight analyses that follow.

3.1 Overview Conceptual Model

The Overview Model represents light pollution as a central stock shaped by flows originating in the built environment and mediated by societal and governance dynamics (Figure 3). Light pollution accumulates as artificial light at night is emitted from built infrastructure — streetlights, commercial facilities, residential properties, sports complexes, and institutional buildings — at intensities and in spectral compositions that exceed ecological thresholds (Hölker et al. 2010b). Dominion Energy functions as an external driver with overarching influence: as the utility responsible for street lighting infrastructure and energy pricing, Dominion's decisions shape what built infrastructure produces light and at what intensity, independent of city-level policy choices.

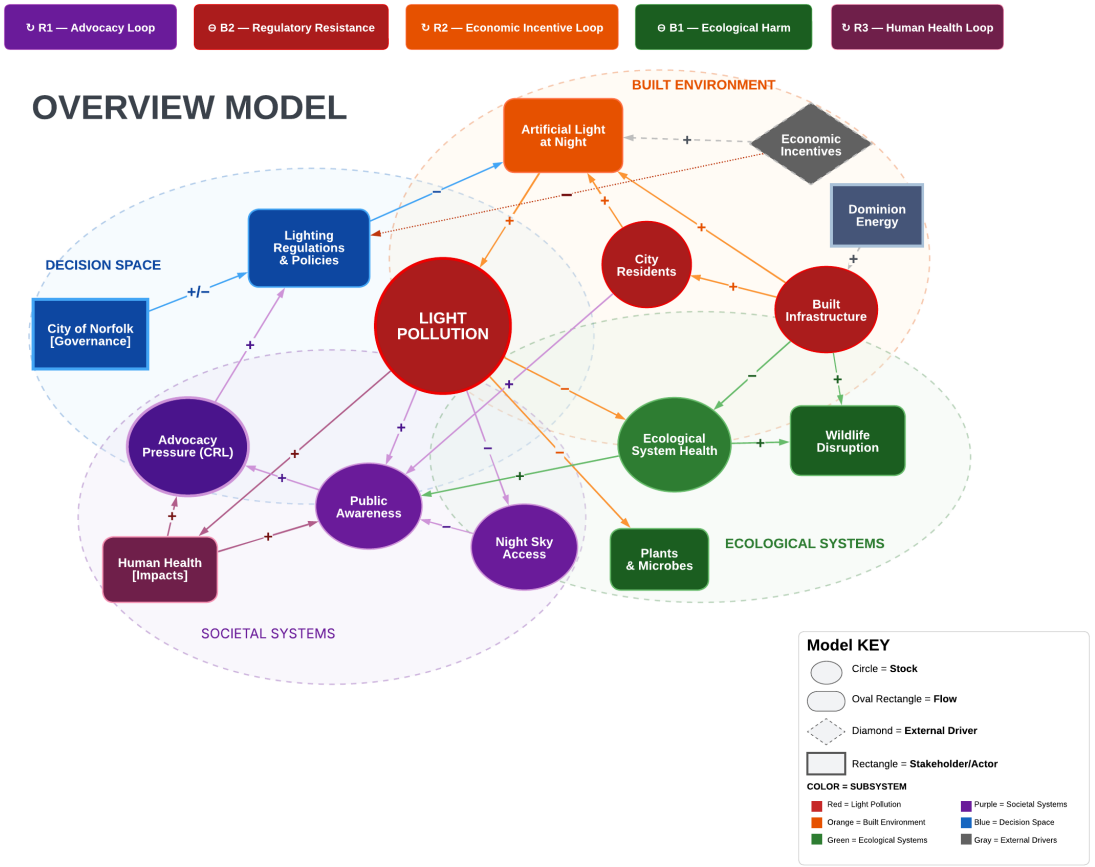

Figure 3: The Overview Conceptual Model illustrates the causal relationships between the built environment, ecological systems, societal dynamics, and governance structures that drive and respond to light pollution in Norfolk, Virginia.

Economic incentives act as a flow amplifying ALAN. Commercial visibility, property security norms, and the economic logic of 24-hour activity all create pressure toward more and brighter light. This dynamic is captured in the Economic Incentive Loop (R2), a reinforcing feedback in which economic activity demands more lighting, which expands built infrastructure, which produces more ALAN. Without countervailing pressure, this loop tends to increase light pollution over time regardless of ecological consequences. The Jevons paradox is evident here: as LED technology reduces the per-unit cost of illumination, the prevailing response is often to install more lighting rather than to bank the savings as reduced output (Kyba et al. 2017).

Lighting regulations and policies from the City of Norfolk represent the primary governance mechanism for moderating ALAN. When regulations are strengthened — driven by advocacy pressure from organizations like CRL — the flow of ALAN from built infrastructure can be reduced. This dynamic forms the Regulatory Resistance Loop (B2), a balancing feedback in which increased advocacy pressure leads to stronger regulations, which reduce ALAN. This loop operates slowly and against significant institutional inertia; regulatory changes require political will, legal authority, and budget capacity that are often in short supply.

The ecological and human consequences of light pollution feed back into the societal system in ways that shape whether advocacy pressure is sustained or grows. Ecological system health declines as ALAN disrupts wildlife behavior, impairs plant and microbial processes, and fragments the nocturnal habitat on which coastal and migratory species depend (Longcore and Rich 2004; Gaston et al. 2013). Wildlife disruption and vegetation impacts are represented as downstream flows — they change slowly but accumulate toward threshold conditions that become increasingly difficult to reverse (Hölker et al. 2010a). As ecological system health declines, public concern grows — this connection is represented in the model as a positive link from Ecological System Health to Public Awareness, completing the Ecological Harm Loop (B1). Declining ecological health visible to residents, scientists, and advocates feeds the awareness stock and strengthens the case for regulatory action.

Human health impacts — including circadian disruption, sleep disturbance, and increased risk of metabolic and cardiovascular disease associated with ALAN exposure — also flow from the light pollution stock (Gaston et al. 2013). These impacts connect to public awareness through the Health Feedback Loop (R3): as health consequences become more documented and visible, public awareness rises, which feeds advocacy pressure, which in turn strengthens the case for regulatory action. This loop runs through the societal subsystem and depends on the quality of light pollution data and the reach of education and outreach efforts.

The mechanisms behind these health impacts are consequential. Chronic ALAN exposure suppresses melatonin production through intrinsically photosensitive retinal ganglion cells, disrupting circadian regulation of sleep, immune function, cell repair, and metabolic processes (Gaston et al. 2013). Epidemiological evidence links persistent nighttime light exposure to elevated risk of breast and prostate cancer, type 2 diabetes, cardiovascular disease, obesity, and depression (Hölker et al. 2010b). These impacts are not evenly distributed. Residents in denser urban neighborhoods experience higher ambient nighttime light levels from streetlights, commercial signage, and traffic, and often have fewer resources to mitigate exposure — making ALAN a question of environmental equity as well as ecological management.

Sleep disruption is the most immediately experienced of these consequences. Melatonin is especially sensitive to short-wavelength blue light, the spectral range that dominates modern LED streetlighting (Gaston et al. 2013). Residents living near unshielded fixtures, commercial corridors, or brightly lit parking areas experience involuntary light exposure that can degrade sleep architecture even when curtains are drawn. Children face heightened vulnerability — nighttime light exposure during critical developmental windows is associated with cognitive and behavioral consequences that can extend into adulthood. Shift workers face compounded risk: their circadian systems are already stressed by irregular schedules and daytime sleep in light-polluted environments.

Night sky access functions as a societal stock that declines as light pollution increases. The loss of visible night sky is not merely aesthetic — it severs a culturally and ecologically significant relationship between human communities and natural darkness (Kyba et al. 2017). Reduced night sky access elevates public concern and feeds into the public awareness stock, contributing to the advocacy chain, though this cultural loss often unfolds on a longer timescale than acute ecological or health harms. City residents are represented as a node within the built environment subsystem. Individual decisions about porch lights, floodlights, decorative lighting, and seasonal installations are shaped both by built infrastructure norms and by public awareness — as awareness increases, resident behavior can shift, reducing unnecessary ALAN at the household level. City residents also connect directly to the public awareness stock: residents who experience glare, light trespass, and disrupted sleep become a constituency for reform, feeding the broader advocacy and regulatory dynamics.

The Overview Model provides the system-wide causal structure from which the subsystem models are derived. Sections 3.2 and 3.3 zoom into two of the subsystems indicated here — the built environment and the ecosystem — tracing at finer resolution the specific pathways by which energy becomes light pollution and by which that pollution propagates through Norfolk's ecological communities.

3.2 Built Environment

The conceptual model in (Figure 5) shows the built environment subsystem indicated in the Overview Model (Figure 3), and the different pathways that energy can take to become light pollution in Norfolk. Dominion Energy acts as the main provider of energy for the City of Norfolk. Dominion Energy has a stock of energy that flows as electricity to stakeholders (blue rectangles) that act as consumers. The energy is then converted to light in different components of the built environment (yellow rectangles). At night, this artificial light is imparted to the rest of the system as light pollution.

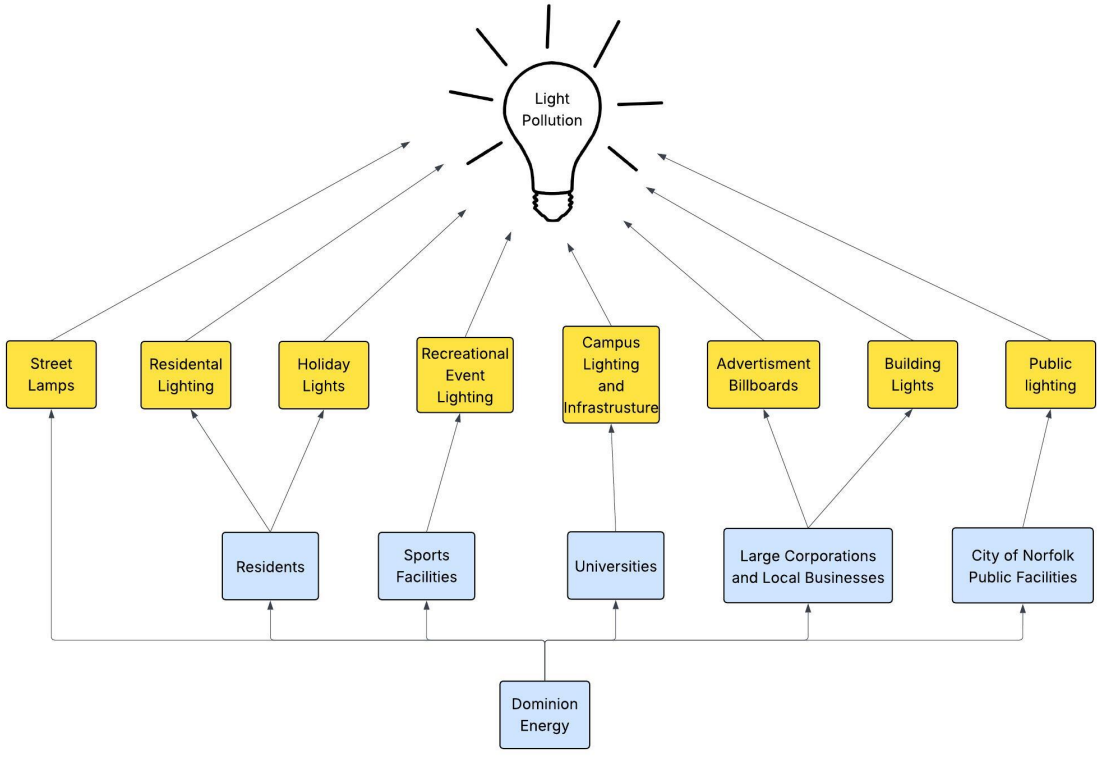

Figure 5: The conceptual model shows the the flow of energy from stakeholders (blue) to the built environment (yellow) which contribute to light pollution.

Dominion Energy has an overarching influence on all other stakeholders, as they are the energy provider, and main legislator of lights and energy in the City of Norfolk. Dominion Energy is also responsible for streetlights in the city. There are different types of streetlights in Norfolk, ranging from acorn style, which contributes the highest amount of light pollution, to fully shielded, which contribute the least light pollution.

Residents of Norfolk have both year-round lighting in and around their homes and may have additional holiday lighting. Residents are responsible for following the 5 principles of outdoor lighting on their own property, whether those lights are permanent or seasonal. Permanent lighting such as porch lights, flood lights, decorative lighting, and indoor lighting that shines through windows are all sources of light pollution. Additional seasonal lighting like spotlights and string lights are also a significant source of ALAN and can add to light pollution depending on the colour and placement of lights.

Norfolk is home to the minor league baseball team the Norfolk Tides, with home games played at the Harbor Park

Stadium. Home games frequently start in the evening and run into nighttime. This requires the field and stadium to be lit, as well as parking lots and the facilities that run the Tide light rail train for safety and transportation of patrons. Other facilities like tennis courts, baseball and soccer fields, and other recreational facilities are also open late into the night, requiring facilities and fields/courts to be artificially lit by large spotlights.

University buildings are also open at night, with the ODU Perry library staying open as late as 12am. This requires that building lights are on, and that lights on campus must be available for students to travel safely to their destination. Universities also have dormitories where residents have the same responsibilities as other residents in Norfolk.

Norfolk is also home to numerous corporations and businesses. It is common to see lit billboards along the road advertising goods and services, and lit signage with the businesses name outside of the business. Storefronts and parking lots outside of businesses are lit for patrons, and some remain lit through the night after closing to deter crime. Notable large corporations in the are area are the Lambert's Point Coal Terminal, the Norfolk Naval Shipyard, Naval Station Norfolk, hospitals, and the Norfolk International Airport.

Many museums, parks, public libraries, theatres, parking garages and parking lots, and the Amtrak station are managed by the City of Norfolk. All of these facilities that are lit at night, with some being lit with decorative outdoor lighting, such as uplighting on the Harrison Opera House, lighting of the reflection pond outside of Chrysler Hall, and lighting atop the Scope Arena, in addition to typical lighting of sidewalks and facility grounds.

3.3 Ecosystem

The conceptual model in figure 6 shows flows from the decision space and external environment to the ecosystem, and between different agents within the ecosystem. The decision space makes the rules and regulations about lighting and decides how lights are used in the built environment, which contribute to light pollution. Migratory birds and insects are free to enter and leave the system and contribute to the stocks of birds and insects in Norfolk. Norfolk is a stopover for migratory birds along the Atlantic Flyway, and is on the migration path for first generation monarch butterflies (Danaus plexippus plexippus) traveling South along the East coast to their overwintering location in Mexico (US Forest Service, 2026).

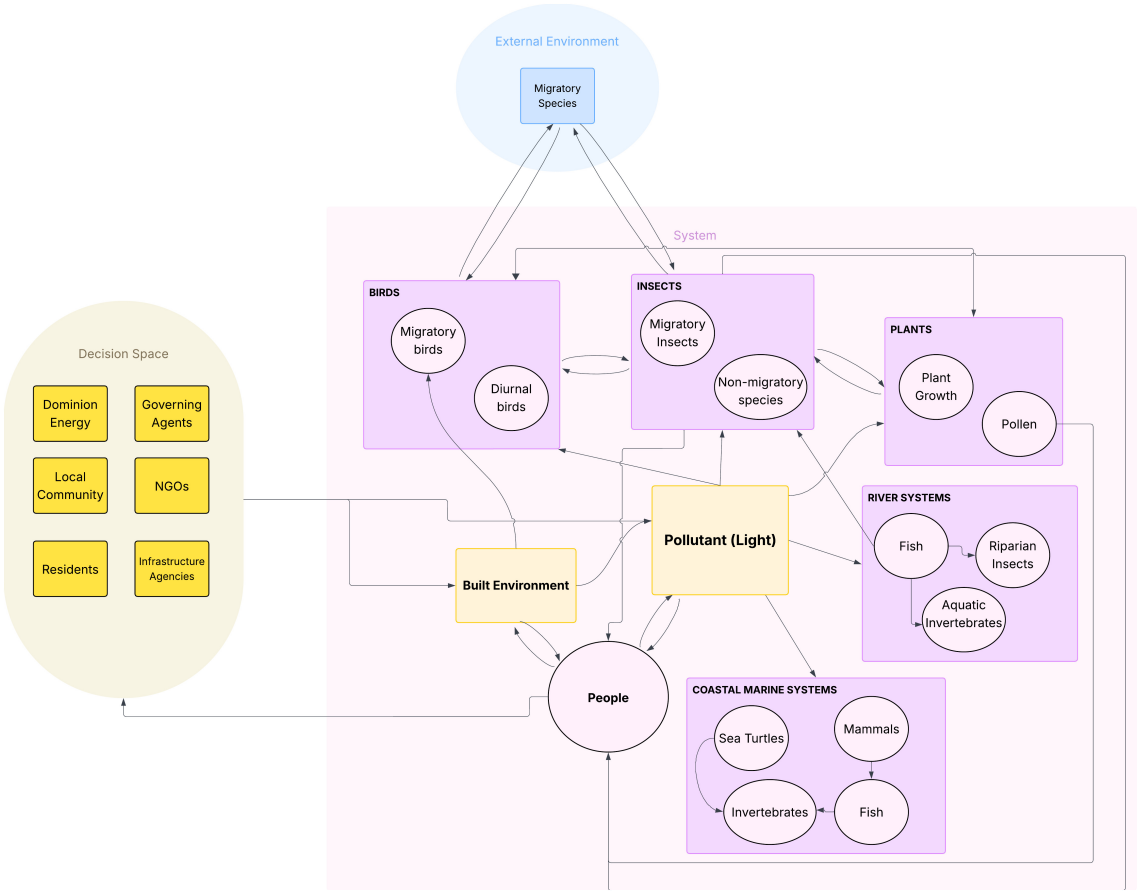

Figure 6: The Ecosystem conceptual model shows the relationships between different sectors of the ecosystem in response to light pollution.

Birds

ALAN can have different effects on diurnal birds. One major effect is reduction in REM sleep at night (Aulsebrook et al., 2021). Passerine birds that experience more REM sleep are better at memorizing the correct species-specific songs, which are critical for attracting mates and defending territory (Aulsebrook et al., 2021). In addition to reduction in REM sleep, birds who are awake at night may be foraging and exerting energy that would otherwise be conserved during sleep (Aulsebrook et al., 2021). These birds will have to spend more time foraging during the day to recoup the costly nighttime energy expenditure, thus reducing the amount of time they spend doing other activities during the day.

For migratory birds, ALAN can be disorienting and alter migratory behaviours. Research suggests that low levels of ALAN cause increased migratory restlessness in Zonotrichia sparrows (Litt-Jukes and Morrissey, 2026). For other species who rely heavily on light for migration cues, high levels of ALAN can supress migratory urges completely. With constant light at night, these birds cannot receive natural photoperiodic cues to trigger migration, and migratory urges

are distorted (Litt-Jukes and Morrissey, 2026). This can cause the birds to migrate too early or late which puts them at risk of encountering phenological mismatch. Arriving at overwintering and breeding sites at the wrong time incurs a timing mismatch between the birds, food availability, and conspecifics which limits potential mates. Furthermore, some migratory species may choose their stopover sites according to the amount of light in the area, limiting the available habitat for certain species like the Eastern whip-poor-wills (Antrostomus vociferus) that prefer dark habitat (Litt-Jukes and Morrissey, 2026).

Artificial light at night can also be an ecological trap for birds. In highly illuminated areas, birds can no longer take cues from the natural environment and are drawn in by the light, causing them to circle the area instead of continuing with on with migration (U.S. Fish and Wildlife Service, 2023). The trapped birds waste their energy needed for migration by circling the area and increase their risk for building strikes. Beyond city skyglow, migration and individual lighted windows correlate strongly with an increase in building strikes and bird mortality (Van Doren et al. 2021).

Terrestrial Invertebrates

In insects and other invertebrates, daily behaviours (i.e. feeding and reproduction) and growth are mediated by photoperiod (Falcón et al. 2026). Monarch butterflies are multi-generational migrants and contribute to the stock of monarchs in Norfolk. While the monarch butterfly migrates during the day, ALAN can disrupt their circadian rhythm and interfere with navigation (Parlin et al. 2022). They provide ecosystem services like pollination of milkweeds and other wildflowers. Populations of monarch butterflies are decreasing and gradually approaching a threshold for extinction (Walker et al., 2022).

The common green darner dragonfly (*Anax junius*) is both a multi-generational migrant and year-round resident that uses the region for breeding. The juveniles of the common green darner are aquatic. The common green darner plays an important role in the trophic system, acting as aquatic predators in the nymph phase, consuming other flying insects and mosquitos- who can be disease vectors- as adults, and are consumed by other predators in higher trophic levels (National Park Service, 2022).

Nocturnal insects are attracted to nighttime light and become trapped by sources of artificial light. LED lamps attract a large number of insects, leading to increased mortality (Falcón et al. 2026).

Plants

Plants have a circadian rhythm that is regulated by light. Altered perceived photoperiod disrupts the natural circadian rhythm, and can change growth rates and timing of bud bursts and cause a phenological mismatch between pollinators and plants, leading to reduced pollination and propagation (Svechkina et al., 2020). Artificial light at night has also been found to extend the length of pollen season. This extended pollen season negatively effects the health of people, causing increased allergy related distress like allergic rhinitis and asthma (Geist et al., 2026).

River Systems

Norfolk is home to the Elizabeth River and its tributaries. These riparian systems are home to fish, and aquatic and emergent invertebrates. The greatest activity of emergent insects is early evening to late morning (Meyer and Sullivan, 2013). ALAN alters the natural light levels during this period and can disrupt dispersal of emergent insects, improve predator efficiency, and attract terrestrial insects to the reflection of light on the water (Meyer and Sullivan, 2013). This disrupts natural trophic dynamics and the flow of energy within the riparian-stream system. When more terrestrial species are attracted to the water, this creates more opportunities for predators to prey upon these species, while releasing aquatic species from predation pressure. Additionally, disruption of emergent insect dispersal increases predation on these species.

Coastal Marine Systems

ALAN has been found to have significant effects on the trophic levels of coastal marine systems. Nocturnally foraging predators have greater success with increased light at night, benefiting from increased visibility of prey, and attraction of prey to light sources (Bolton et al. 2016). ALAN also changes the use of habitat for fish. Where they use certain habitat for shelter under a dark sky, they use the same habitat for foraging in the presence of light pollution (Bolton et al. 2016). The change in habitat use and increased predation alters the stocks of predators and prey, including the stocks of small fish and invertebrates, and cetaceans that prey on fish.

In addition to the fully aquatic species of fish and mammals found in the coastal waters, five species of sea turtle can be found in the Chesapeake Bay region, with the loggerhead sea turtle (*Caretta caretta*) commonly nesting on Virginia shores (Virginia Department of Wildlife Resources, 2016). ALAN repels female turtles searching for undisturbed nesting sites and disorients loggerhead hatchlings away from the ocean where they are vulnerable to predators (Miller and Rice, 2023).

People

As mentioned in section 3.1, the health consequences of ALAN can be widespread, disrupting he circadian rhythm and sleep, and causing tumours, higher body mass, and depression (Svechkina et al., 2020).

Importantly, ALAN causes decreased visibility of the night sky. People in Norfolk are robbed of the experience of seeing stars and space. Younger generations are disparately affected because they cannot go outside to look at the night sky the same way that older generations used to. Citizen science contributes heavily to the field of astronomy, identifying meteors, asteroids, and other events in space. Science suffers when citizens cannot participate, and it creates a disconnect between people, science, and the natural world.

3.4 Decision Space Conceptual Model

Where the Overview Model traces system-wide causal structure, the Decision Space Model maps the governance and advocacy architecture that determines whether interventions to reduce light pollution can move from proposal to implementation (Figure 4). Light pollution remains the central stock, but this model foregrounds the actors, institutions, rules, and information flows that shape how and whether decisions to address it can actually be made (Plag 2024).

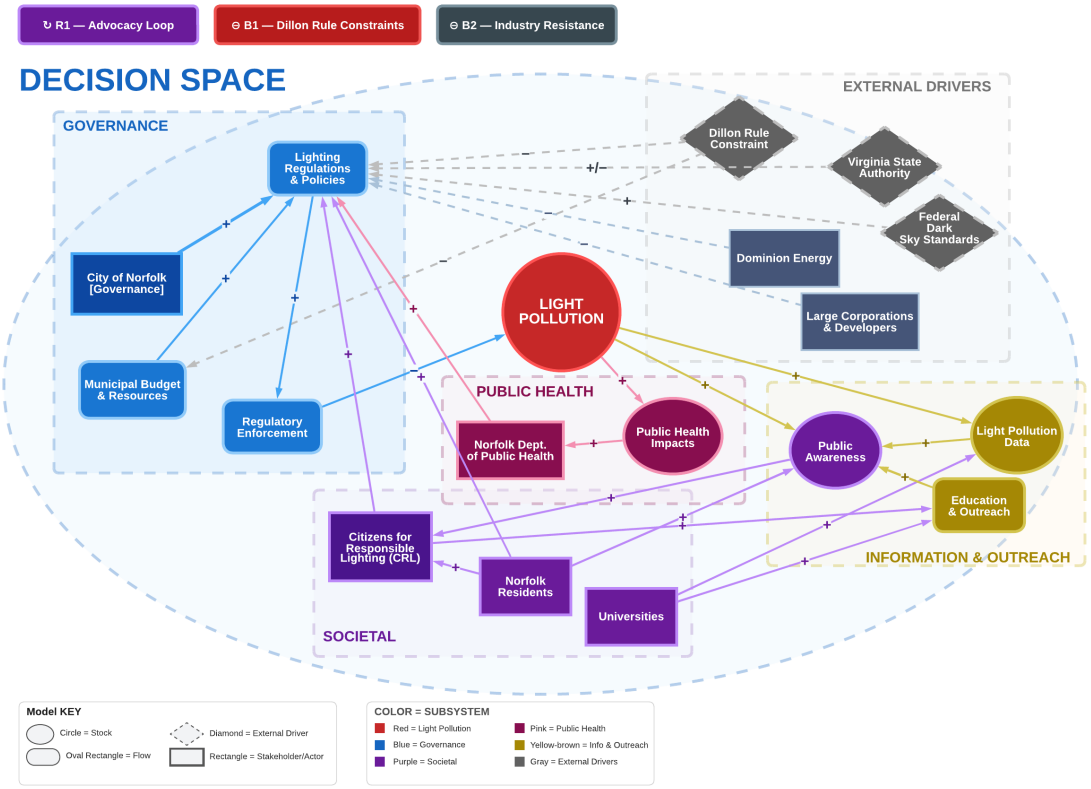

Figure 4: The Decision Space Conceptual Model maps the governance, advocacy, and information pathways that shape decision-making around light pollution in Norfolk, Virginia, including key feedback loops and institutional constraints.

The governance subsystem is anchored by the City of Norfolk, whose capacity to act is shaped by three interacting flows: lighting regulations and policies, municipal budget and resources, and regulatory enforcement. These three flows are not independent. The Dillon Rule Constraint (B1) is a structural balancing loop: as Norfolk's regulatory ambition increases, the legal limits imposed by Virginia's Dillon Rule doctrine push back, restricting the city's authority to mandates that are expressly granted by state law. This constraint is represented as a dedicated node because it is one of the most consequential structural features of Norfolk's decision space — it means that the most direct levers for lighting reform must pass through or around state-level authority.

Virginia State Authority sits above the city as an external driver shaping what municipal governance can do. Federal Dark Sky Standards function as an additional external driver — providing scientific and policy benchmarks that advocacy organizations can invoke but that carry no binding enforcement power at the local level. These external drivers illustrate the multi-scalar nature of the governance problem: local actors operate within state constraints, state actors operate within federal frameworks, and none of these levels has comprehensive jurisdiction over the full built environment.

Dominion Energy appears in the Decision Space Model as a private industry actor whose cooperation is functionally required for any large-scale streetlight transition. The Industry Resistance Loop (B2) captures the dynamic by which industry actors apply pressure — through contract terms, cost arguments, and regulatory relationships — that limits how aggressively the city can mandate changes. Large corporations and developers operate similarly: their interest in commercial visibility and lighting norms creates counterpressure against restrictions on outdoor lighting.

The societal subsystem connects residents, universities, and CRL through public awareness and the information and outreach infrastructure that sustains it. Universities contribute to light pollution data generation and education and outreach programs, feeding the information base on which advocacy depends. Norfolk residents shape and are shaped by public awareness — as awareness grows, residents become a constituency for reform and a base for CRL's advocacy work. The Advocacy Loop (R1) is the primary reinforcing dynamic in the Decision Space: CRL and allied organizations generate advocacy pressure, which creates political demand for regulatory action, which when successful reduces light pollution — and the demonstrated possibility of change sustains and builds the advocacy coalition.

Public health impacts are represented as a distinct subsystem. Light pollution drives public health impacts — including sleep disruption, circadian harm, and associated chronic disease risk — which are tracked and responded to by the Norfolk Department of Public Health. The Department connects directly to lighting regulations and policies, representing the pathway by which documented health consequences enter the formal governance process and create institutional pressure for reform (Gaston et al. 2013; Hölker et al. 2010b).

The Decision Space Model makes visible what the Overview Model treats as background: the governance constraints, the institutional veto actors, and the information and advocacy pathways that determine whether any intervention can actually move from proposal to implementation. No lever exists in isolation. Regulatory enforcement requires municipal budget; budget requires political will; political will requires public awareness; public awareness requires data, outreach, and a community of people who understand what is at stake. This interdependence is the structural signature of a wicked problem — and it is where the case for coordinated, multi-level intervention rests (Rittel and Webber 1973; Kolko 2012).

4 Exposed Assets

Abby Lahey

Identifying exposed assets in a light pollution case study requires a different framing than most environmental risk assessments. In cases involving flood, storm surge, or chemical contamination, exposed assets are typically defined as physical infrastructure, property, or ecosystems positioned in the path of an external hazard. Light pollution inverts this structure. ALAN is generated from within the system by the very infrastructure and institutions that serve human needs — and the assets exposed to it are the living systems, human communities, and ecological processes that depend on natural darkness to function (Hölker et al. 2010a; Longcore and Rich 2004). The hazard is not arriving from outside. It is being produced continuously, everywhere, by the built environment itself.

This distinction matters for how exposure is assessed. The relevant question is not where the hazard will strike, but which components of the socio-ecological system are most sensitive to ALAN, least able to avoid or adapt to it, and most consequentially harmed when exposed to it (Gaston et al. 2013). Norfolk's exposed assets span ecological, human health, and cultural dimensions — and in many cases, the same communities and species that are most exposed are also least positioned to advocate for protection.

4.1 Migratory and Nocturnal Wildlife

Migratory birds are among the most severely exposed assets in Norfolk's lighting landscape. The Atlantic Flyway passes directly over the Hampton Roads region, and millions of birds navigate through or around the area each year using celestial cues and natural darkness (Longcore and Rich 2004). Skyglow from urban areas disorients migrating birds, causing them to circle illuminated structures, collide with buildings, and exhaust critical energy reserves. Norfolk International Airport, the downtown waterfront, and the dense commercial corridors along major roadways all represent significant collision and disorientation hazards during peak migration windows. Longcore and Rich (2004) document that building strikes — driven largely by artificial light attraction — kill hundreds of millions of birds annually in North America, making ALAN one of the leading anthropogenic causes of avian mortality.

Insects, particularly pollinators, are acutely sensitive to artificial light at night. Nocturnal pollinators including moths orient by natural light gradients and are drawn to artificial sources, disrupting foraging behavior and reducing pollination services to native plant communities (Hölker et al. 2010b). Knop et al. (2017) found that nocturnal pollinator visits to illuminated plants were substantially reduced relative to unlit controls, with measurable reductions in fruit set in affected plant communities. Given Norfolk's position within the Chesapeake Bay watershed — where coastal plant communities, wetland vegetation, and urban greenspace all depend on pollinator activity — the exposure of insect communities to ALAN represents a functional loss of ecosystem services, not merely a biodiversity concern.

Bats, which play critical roles in insect population regulation and ecosystem balance, show strong behavioral responses to ALAN. Many bat species avoid lit areas entirely, effectively losing foraging habitat as urban light expands (Hölker et al. 2010a). Sea turtles nesting along Virginia Beach and the lower Chesapeake coast are disoriented by coastal light pollution during nesting season, leading hatchlings to move toward artificial light rather than toward the ocean — a well-documented mortality pathway (Longcore and Rich 2004). Fish and aquatic life in the Elizabeth River and adjacent estuarine systems are exposed to ALAN through bridge lighting, waterfront development, and marina infrastructure, with documented effects on feeding behavior, predator-prey dynamics, and reproductive cycles (Gaston et al. 2013).

4.2 Urban Ecosystems and Ecosystem Services

The broader ecological system of Norfolk — tidal wetlands, riparian corridors, urban tree canopy, and coastal scrub habitat — functions as an interconnected web of services: water filtration, carbon sequestration, habitat provision, shoreline stabilization, and cultural value. ALAN disrupts the phenological cues that coordinate biological timing across these systems. Plant flowering, leaf-out, and dormancy cycles are regulated in part by photoperiod; chronic light exposure alters these rhythms, creating mismatches between plants and their pollinators, herbivores, and seed dispersers (Gaston et al. 2013). As photoperiod-driven timing is altered, plants and their pollinators, herbivores, and seed dispersers fall out of sync, and over time this changes which species persist and how reliably the system provides habitat, carbon storage, and water regulation.

Trophic relationships are particularly vulnerable. Disruption to nocturnal insect communities removes prey from higher trophic levels — bats, songbirds, and amphibians — whose populations decline in ways that are spatially diffuse and temporally delayed relative to the original light exposure (Hölker et al. 2010a). The Elizabeth River and Chesapeake Bay estuarine systems, already stressed by nutrient loading and legacy contamination, are exposed to additional ALAN pressure from waterfront development, the port complex, and recreational boating infrastructure. These systems have limited redundancy; species assemblages that are already compressed by habitat loss and water quality degradation have reduced capacity to absorb additional photonic stress.

4.3 Human Health

Human health is a directly exposed asset in ways that are often underappreciated in public discourse about light pollution. ALAN suppresses melatonin production through the photoreceptive cells of the retina, disrupting circadian rhythms with measurable consequences for sleep quality, immune function, metabolic regulation, and cardiovascular health (Gaston et al. 2013). Epidemiological evidence links chronic nighttime light exposure to elevated risk of breast and prostate cancer, type 2 diabetes, obesity, and depression (Hölker et al. 2010b). These health effects are not uniformly distributed. Residents in denser urban neighborhoods — including many lower-income communities in Norfolk — are exposed to higher ambient nighttime light levels from streetlights, commercial signage, and traffic, with fewer resources to mitigate exposure through blackout curtains, relocation, or built environment modification.

Shift workers, children, and elderly residents are disproportionately vulnerable to circadian disruption from ALAN. For children, nighttime light exposure during critical developmental windows carries particular significance: sleep disruption during childhood is associated with cognitive and behavioral consequences that extend into adulthood. Norfolk's exposure profile is not evenly distributed across the population — communities with less political capital and less control over their built environment bear more of the health burden while having the least ability to shape the lighting decisions that create it.

4.4 Night Sky and Cultural Connection

The night sky itself is an exposed asset — one that is culturally, scientifically, and psychologically significant. Access to natural darkness and a visible night sky has historically connected human communities to ecological rhythms,

navigational knowledge, cultural stories, and a sense of scale and place within the natural world (Kyba et al. 2017). As skyglow has expanded, this access has been progressively eroded for urban populations. For most Norfolk residents, a naturally dark sky is not a lived experience but an abstraction — something encountered only on trips outside the region. Kyba et al. (2017) document that the artificially lit area of the Earth's surface is increasing annually, meaning that each generation of urban children grows up with less access to natural darkness than the last.

This loss is difficult to quantify but real in its consequences. Amateur astronomers, educators, and communities who rely on night sky visibility for practice and transmission of knowledge are directly affected. More broadly, the severing of urban populations from natural darkness contributes to a declining capacity to perceive, interpret, and value the nonhuman world (Longcore and Rich 2004). This cultural exposure compounds the ecological and health exposures described above; communities that cannot see the night sky are less likely to recognize what is being lost and less likely to mobilize around its protection.

4.5 Assets Sustained by Artificial Light

Norfolk's economy, public safety, and daily life depend on artificial light, and a substantial share of activity would contract or fail without it. The exposure ledger has two sides, and any honest accounting has to hold both.

The historical arc is long. For most of human history, the supply of light tracked the supply of wealth. Candles, oil lamps, and kerosene were rationed by household budget, and the people who could read, work, or move through a city after sunset were the ones who could afford the fuel. Electrification broke that constraint at municipal scale, and cheap LED lighting drove the marginal cost of a lumen close to zero. Kyba et al. (2017) documented that Earth's artificially lit area is growing at roughly two percent per year, the trajectory of a technology that has overshot the conditions it was deployed to address.

Some of that dependence is harder to substitute than comprehensive lists suggest. Shift change at Norfolk Naval Shipyard happens in full dark for half the year, and the workforce crossing parking lots and gates depends on visibility no policy can compress into daylight. Port operations on the Elizabeth River run on tidal schedules that ignore the solar calendar. Low-vision residents at Hampton Roads Transit stops need consistent illumination to identify curbs and route signage at distances their vision can resolve.

Crime is the asset most often invoked in defense of more light, and the evidence is more complicated than the rhetoric. Total darkness does not eliminate crime. It shifts where crime occurs. Chafin et al. (2021) found that during prolonged streetlight outages, crime volume did not increase, but the distribution moved closer to the area of outage. The policy question is whether the current quantity, spectrum, and distribution of light serve the safety claims made for it.

Light itself is not the hazard, but rather, artificial light that is deployed without consideration, accountability, or limit. These factors are what separate light that serves the city from light that produces the harms traced through this report. Sections 7 and 9 take up that range.

5 Identifying System Fragilities

Abby Lahey, Danielle Delp

Fragilities are the weak spots in a system — the places where things give way when they are stressed. ALAN is the hazard, but the parts of Norfolk’s lighting system that cannot resist or recover from that hazard are the fragilities. These weak spots show up in laws and budgets, in stressed ecosystems, in social inequalities, and in the fixtures and poles that make up the built environment. Many of them have been built in over decades, as lighting spread across the city with little attention to ecology or public health (Hölker et al. 2010a; Rittel and Webber 1973).

5.1 Governance Fragilities

Some of the most important weak spots in Norfolk’s lighting system are not physical at all — they are built into the way the city is allowed to govern. Virginia’s Dillon Rule means that Norfolk can only exercise powers the General Assembly has clearly granted (Va. Code §15.2-2280). In practice, this keeps the city from setting its own lighting standards on military property, changing Dominion Energy’s tariff structure without a full SCC rate case, or passing ordinances that go beyond state enabling legislation. The city can see problems it is not fully allowed to fix, and no amount of local political will can erase that constraint.

At the same time, this legal framework leaves at least one pathway partly open. Norfolk still has a responsibility to protect public health, even within Dillon Rule limits. As evidence grows that artificial light at night can disrupt circadian rhythms, suppress melatonin, and contribute to chronic disease risk, the city may be able to use its public-health authority to regulate certain lighting conditions that it cannot reach through zoning alone. This idea has not yet been tested in Norfolk’s lighting governance, and it would require careful legal groundwork, but its absence from current conversations suggests a missed leverage point.

Fragmented authority makes these constraints harder to work around. No single agency in Norfolk is responsible for “the lighting system” as a whole. Public Works and Planning oversee some parts of municipal lighting, but Dominion Energy, VDOT, the military, private property owners, and commercial developers all control their own installations and standards. Each actor makes decisions that make sense within their own mandate; together, those choices add up to a system that no one fully oversees or is accountable for. Longcore and Rich (2004) describe this kind of fragmentation as a core obstacle in urban light-pollution governance: when no agency owns the whole problem, the work of pushing for change often falls to advocacy groups that have knowledge but no formal power.

Procurement practices introduce another weak spot. Public contracts often prioritize the lowest upfront cost and operational simplicity over ecological or health performance. When Norfolk upgrades lighting under this logic, fixtures may be chosen for price and efficiency without regard for spectral quality, directionality, or adaptive controls. LED retrofits, for example, can reduce energy use but still increase biologically disruptive blue-rich emissions if they are not specified carefully (Kyba et al. 2017). Because the city’s procurement process does not systematically screen lighting specifications for ecological or health impacts, efficiency upgrades can unintentionally deepen the biological impacts of ALAN even as they lower the utility bill.

Fiscal limits further narrow the city’s options. Every potential intervention costs something — new fixtures, adaptive control systems, staff to write and enforce ordinances, community engagement — and those costs compete with other urgent needs, including coastal flood management, aging infrastructure, and social services. Responsible lighting has

not historically been framed as a core infrastructure or health investment. Without dedicated funding streams or strong state and federal incentives, even motivated city staff face hard trade-offs that keep lighting reforms on the margins.

Finally, Norfolk is trying to manage light pollution without systematic baseline data. The city does not have comprehensive measurements of ALAN intensity, spectral composition, or spatial distribution across neighborhoods, transportation corridors, or ecologically sensitive areas. Without that baseline, it is difficult to quantify the current state of the problem, track changes over time, evaluate interventions, or compare conditions between different parts of the city. In the Decision Space Model (Figure 4), this shows up at the Light Pollution Data node, where the quality and availability of data shape public awareness, advocacy, and the strength of the case for regulatory action. Governing light pollution without measurement is like managing water quality without ever testing the water.

5.2 Ecological Fragilities

The ecological systems most exposed to ALAN in and around Norfolk are already under pressure from multiple other stressors. The Elizabeth River and Chesapeake Bay watershed have experienced decades of nutrient loading, legacy contamination, shoreline development, and habitat loss (Longcore and Rich 2004). Species assemblages squeezed by these pressures have less redundancy and less capacity to absorb additional disruption. When an ecosystem is already operating near its functional limits, even modest increases in artificial light can push populations and communities past critical tipping points (Hölker et al. 2010a).

For the plants and animals in these systems, the ability to sense light appropriately is fundamental. Photoreceptors are specialized cells that detect different wavelengths of light. They are located in the retinas of vertebrates, the compound eyes of insects, various tissues of plants, and in other body surfaces for invertebrates that lack eyes, such as the skin of earthworms. These photoreceptors send signals to the systems in the body that regulate sleep-wake cycles, migration timing, reproduction, and many other processes. Under Earth's natural photoperiod, those signals are predictable and aligned with day-night cycles. When light is present at times when darkness would normally occur, these systems can no longer send signals at the right time, leading to disorientation and physiological stress.

This dependence on light-sensing cells is a fragility that cuts across many groups of organisms at once. Vertebrates, insects, plants, and marine invertebrates all rely on photoreceptive systems that evolved under stable light-dark cycles and have limited capacity to adapt to constant or badly timed artificial illumination. ALAN thus affects not just individual behaviors, but the sensory architecture organisms use to coordinate some of the most basic aspects of their biology.

Migratory birds are especially vulnerable in a temporal sense. The periods when disorientation and collision risk are highest — spring and fall migration — are narrow but biologically crucial. A single night with heavy migratory traffic combined with bright, persistent lighting can cause substantial mortality, and those losses may take years to appear clearly in population data (Gaston et al. 2013). Many of these species move along the Atlantic Flyway, a corridor that funnels birds from across northeastern North America along the Virginia coast in fall and back again in spring. The reliance on this pathway and its limited stopover options add to the fragility: each brightly lit building, bridge approach, or industrial site along the corridor becomes a potential hazard, and there are few alternative routes.

Pollinator communities face a similar compounding pattern. Insects in urban and peri-urban landscapes are not just dealing with ALAN; they are also coping with pesticide exposure, habitat fragmentation, invasive species, and climate change. The interaction of these stressors creates what the section on governance might call "causal complexity," and here that complexity is itself a fragility. When multiple drivers act at once, it becomes methodologically difficult to isolate how much of an observed decline is due to light pollution versus other pressures. That difficulty, in turn, weakens the regulatory case for addressing ALAN directly. Light becomes one more factor in a long list, rather than a clearly identified cause that demands targeted action.

This dynamic extends beyond pollinators. Across the Elizabeth River watershed, the Chesapeake Bay estuary, and Norfolk's urban greenspaces, ALAN interacts with nutrient loading, contamination, habitat fragmentation, and climate-driven changes in ways that make its individual contribution hard to isolate and easy to postpone. The result is an ongoing accumulation of ecological risk.

5.3 Social and Behavioral Fragilities

Low public awareness of light pollution's ecological and health impacts is a foundational social fragility. Unlike air or water pollution, ALAN does not usually produce dramatic spills, visible plumes, or acute crises that force attention. Its effects build slowly, spread across space, and often stay below the threshold of conscious experience for most urban residents (Kyba et al. 2017). As a result, the group of people who see light pollution as a serious problem is small compared to the number of people who are affected by it. It is concentrated in advocacy organizations, researchers, and individuals who have encountered the issue through their own health, work, or night sky experiences.

Cultural norms reinforce this lack of awareness. For generations, artificial light has been treated as a sign of safety, progress, and economic vitality. Many urban residents have never known a truly dark sky, so spaces that are dimmer or intentionally dark can feel unusual or unsafe rather than restorative (Longcore and Rich 2004). The belief that "brighter equals safer" is not just a slogan; it shows up in neighborhood meetings, planning hearings, and everyday conversations whenever lighting is discussed. Lighting manufacturers, law enforcement, and municipal messaging have all helped cement this idea over decades.

This belief also carries a gendered dimension. The claim that women need more lighting for safety is rarely questioned in public discourse, even though the relationship between illumination levels and actual crime reduction is more complicated than the rhetoric suggests. This makes proposals to dim or remove lights politically sensitive, particularly in communities where people already feel vulnerable at night. Any change that looks like "less light" can be interpreted as "less safety," even if the evidence does not fully support that assumption.

Environmental justice dynamics add another layer of fragility. Low-income communities in Norfolk are often more heavily lit, have less control over their surroundings, and have fewer resources to mitigate exposure. Higher streetlight densities, nearby commercial corridors, and security lighting can all increase nighttime brightness in these neighborhoods. Renters experience a specific form of disempowerment: exterior lighting is usually controlled by landlords or property managers, and tenants often have no formal mechanism to request changes to fixtures that shine directly into their windows or keep bedrooms bright at night. At the same time, these communities have historically had less access to decision-making processes about infrastructure, including lighting (Gaston et al. 2013). Those who experience the most light at night often have the least influence over how much light there is. That mismatch weakens the system's ability to correct itself from within.

5.4 Built Environment Fragilities

Norfolk's existing lighting infrastructure is itself a major fragility. The city's streetlights and outdoor fixtures form a patchwork of technologies, designs, and ages, from older high-pressure sodium fixtures and warmer-toned LEDs to decorative acorn-style and blue-rich LEDs that produce more skyglow and biologically disruptive short-wavelength light (Kyba et al. 2017). Each type has its own spectral profile, glare characteristics, and replacement timeline.

Infrastructure lock-in makes this patchwork hard to change quickly. Streetlights and large-scale installations are designed to last for many years. Contracts with utilities and vendors can be complex and inflexible. Recent investments in LED conversions, even when the chosen fixtures are not ecologically ideal, create institutional reluctance to revisit those decisions. Once a particular fixture type or contract structure is in place, changing course requires additional money, staff time, and justification.

This is an example of path dependency: early choices about fixture types, contract terms, and design standards set a path that later decisions tend to follow. It is often easier to repeat what has already been done than to stop and renegotiate the basic approach to lighting.

The transition to LEDs also reveals a Jevons paradox in the lighting system. When lighting becomes cheaper to provide, cities and property owners rarely stop at delivering the same amount of light more efficiently. Instead, they often add more fixtures, keep lights on longer, or expand illuminated areas. Efficiency gains are reinvested into more light rather than less. Kyba et al. (2017) show that globally, artificially lit outdoor areas have continued to increase in both brightness and extent despite widespread adoption of LEDs. In other words, the technology that could help reduce ALAN can also accelerate it if nothing else in the system changes.

Finally, the limited use of adaptive lighting controls across the city represents a missed opportunity. Technologies that allow dimming, curfews, motion-based activation, or seasonal adjustments are available and increasingly common in other contexts. They could reduce light levels during low-traffic hours, migration windows, or sensitive breeding seasons without compromising safety or basic functionality. Where these tools are not used, Norfolk's lighting operates at or near the same intensity night after night, regardless of who is outside or what is happening in the surrounding ecosystems. Cost concerns, existing procurement practices, and lack of integrated planning all contribute to this gap.

6 Current and Future Hazards and Threats

Danielle Delp, Abby Lahey, Jamie Heffernan

ALAN is unlike most of the hazards environmental case studies are built to analyze. It is not a pollutant in the conventional sense, it is not tied to a single industry or responsible party, and the same infrastructure producing it is infrastructure that Norfolk's residents, businesses, and institutions actively depend on. That last point is what separates ALAN from most other urban environmental hazards: the source cannot be fully eliminated, only reshaped in how it is governed and operates. The sections below examine the biological and ecological chains through which ALAN causes harm, the institutional and regulatory conditions that allow it to persist, the technological pressures accelerating it, and the quantitative trajectory of radiance in Norfolk over the coming decades. Table 9 links the frgilities outlined in section 5 with their associated hazard and how those fragilites are affected.

Table 9: The table links fragilites from section 5 with the hazards that can impose upon them.

Fragility	Associated Hazard	Explanation
Fragmented governance	Lack of a central authority	No single authority has the jurisdiction to create regulations regarding how much light is allowed in the city.
Photoreceptors and associated internal functioning	ALAN	Natural light is obscured by ALAN creating an ecological trap for nocturnal pollinators.
		Marine predator-prey dynamics are altered as prey species are attracted to ALAN.
		ALAN causes phenological mismatch between plants and pollinators, and between migrants and food sources.
		Increased blue light supresses melatonin, disrupting sleep and immune function.
Dependence on the Atlantic Flyway	ALAN	ALAN causes disorientation of migratory birds and increases building-strike mortality.
Existing infrastructure and age of technology	Replacement of outdated technology with more efficient LEDs	LED lights emit brighter and more blue-rich light.

6.1 Institutional and Regulatory Hazards

The institutional landscape around lighting in Norfolk is a hazard in its own right. No single municipal ordinance addresses light pollution directly, which means lighting decisions happen under procurement logic, zoning precedent, and safety liability frameworks that were never designed with ecological or circadian health in mind (Rittel and Webber 1973). The rules that do exist are scattered across building codes, zoning regulations, and industry design standards. In the absence of a designated authority, the cumulative light environment becomes an orphaned outcome.

Liability frameworks compound the problem by pulling in the wrong direction. Municipal lighting practices are measured against engineering standards like the Illuminating Engineering Society's RP-8 roadway lighting guidelines (Illuminating Engineering Society 2014), which means a city that deviates from those standards — even to reduce ecological and public health harm — takes on legal exposure that a city maintaining the status quo does not. Responsible lighting, in this framework, becomes a liability risk. The logic of tort protection is structurally biased toward more light, not less, and it is one of the clearest examples of how institutional design can override scientific evidence.

Regulatory fragmentation creates a hazard of omission. No single agency is responsible for the cumulative light environment of the city, which means no agency is accountable when that environment causes harm. Dominion Energy manages street lighting contracts but is not responsible for ecological outcomes. The City of Norfolk manages zoning but cannot regulate military or state-controlled property. VDOT controls roadway lighting but prioritizes traffic flow and

driver visibility over ecological sensitivity. The military manages its installations under federal authority that operates entirely outside city jurisdiction. Each actor can accurately say the problem exceeds its mandate, and the gaps between those mandates are where light pollution accumulates without governance (Kolko 2012).

The commercial space sector represents an emerging governance hazard with no regulatory framework at all. Reflect Orbital, a California-based startup, has proposed a constellation of orbital reflector satellites designed to redirect sunlight to Earth's surface after dark for commercial solar energy and nighttime illumination, with plans for up to 4,000 satellites in orbit by 2030 (Skibba 2025). The first test satellite, Earendil-1, is scheduled for launch in 2026 and will reflect sunlight at intensities comparable to a full moon. If this constellation is deployed at scale, it would dramatically increase skyglow across entire regions, and no city or state has the authority to say no. The Federal Communications Commission oversees satellite communications but not reflected sunlight, and the gap between those jurisdictions is where this hazard lives. The proposal illustrates how lighting governance problems extend well beyond the built environment into domains that existing regulatory architecture was never designed to address, and it is a concrete example of how clean energy innovation can generate externalities that overwhelm the protective frameworks local communities depend on.

These institutional and regulatory gaps do not self-correct. Each one — liability logic that rewards brightness, fragmented jurisdiction that diffuses accountability, emerging technologies that outpace governance — reinforces the others, and the cumulative effect is a regulatory environment that cannot respond to a hazard it was never designed to recognize.

6.2 Artificial Light at Night

Artificial light at night is the central hazard in this system, and it behaves differently than the hazards most environmental case studies describe. It does not arrive from outside, it does not concentrate in a single event, and it does not stop. Norfolk generates it continuously — from streetlights and stadium lights, from the waterfront infrastructure that lines the Elizabeth River, from the commercial corridors and residential streets that stay lit through the overnight hours. The harm moves through the same biological channel that natural light has always used to sustain living systems. Light is the primary zeitgeber that synchronizes circadian rhythms for virtually all complex organisms (Hölker et al. 2010a), and when artificial sources distort that cue across hours when darkness is biologically expected, the consequences travel through five cascading chains that connect individual organisms to the larger ecological community.

The first chain begins with nocturnal pollinators. Moths and other night-active insects evolved to navigate using natural light gradients, and artificial fixtures overwhelm those gradients, drawing insects toward bulbs where they exhaust themselves rather than visit the plants that depend on them. Knop et al. (2017) found that illuminated plants received substantially fewer nocturnal pollinator visits than unlit controls, along with measurable reductions in fruit set. Those reductions carry forward through the food web, because seeds and fruit feed the animals that feed other animals. The nocturnal portion of pollination work is largely invisible to policy attention because it happens in the dark, but the ecological productivity it supports is real and irreplaceable (Hölker et al. 2010a).

The second chain runs along the waterfront, where Norfolk's bridges, marinas, commercial piers, and lit riverside development reach directly over the Elizabeth River and its tributaries. Manfrin et al. (2017) documented that aquatic insect emergence roughly doubles at lit riparian sites, with riparian spiders and ground beetles responding by extending their activity periods and growing in abundance. In follow-up work using stable isotope analysis, Manfrin et al. (2018) showed that riparian spider diets shifted toward significantly greater aquatic prey assimilation under ALAN, indicating that light is not just rearranging where animals are but what they eat and how energy flows between aquatic and terrestrial systems. In a river already burdened by nutrient loading and legacy contamination, this becomes another stressor with no identifiable source or responsible party.

The third chain begins with migratory birds. Norfolk sits on the Atlantic Flyway, which means millions of night-migrating birds pass through the region twice each year, navigating by celestial and magnetic cues that urban skyglow degrades. Disoriented birds are drawn toward illuminated buildings, towers, and sports facilities, where they collide with glass, circle until their energy reserves fail, or lose the navigational thread that would have carried them to breeding grounds (Longcore and Rich 2004). The mortality compounds across years into population-level declines that no single city can be blamed for and no single night can explain. Because birds are major insect predators, the same light that kills them also weakens the top-down pressure those birds would have placed on insect populations below them, reshaping regulation across two trophic levels at once.

The fourth chain runs through the human population. ALAN suppresses melatonin production through the photoreceptive retinal cells that are especially sensitive to short-wavelength blue light — the spectral range dominating modern LED fixtures (Gaston et al. 2013). Disrupted melatonin disrupts sleep architecture, immune function, metabolic regulation, and hormonal balance, which is why chronic nighttime light exposure has been associated with elevated rates of breast cancer, prostate cancer, type 2 diabetes, cardiovascular disease, obesity, and depression (Hölker et al. 2010b). These outcomes fall hardest on residents of densely lit neighborhoods, on shift workers, and on the communities with the least capacity to control the lighting in their own environments.

The fifth chain is phenological, and it operates across all of the others. Plants, insects, birds, and many other organisms coordinate flowering, hatching, migration, and reproduction using photoperiod as a timing cue (Gaston et al. 2013). When ALAN distorts that cue, biological calendars drift out of alignment across species that evolved to move in step with one another. A plant may flower before its pollinator emerges. A migratory bird may arrive at breeding grounds after the insect peak has passed. No single mismatch looks like a crisis, but the coordination that sustains ecological relationships depends on those alignments, and each season spent out of rhythm costs the system something it cannot easily recover.

These chains do not operate independently. Underwood et al. (2017) showed that ALAN-acclimated dog whelks displayed increased hunting behavior in the presence of predator cues and were less likely to seek refuge at the waterline — a basic alteration of the predator-prey dynamic that structures intertidal communities. When behavioral and demographic shifts like this occur simultaneously across pollinators, riparian invertebrates, migratory birds, and people, the combined effect is the restructuring of trophic relationships across the ecological community. Norfolk's place within the Chesapeake Bay watershed, where the estuarine food web is already compressed by nutrient loading, hypoxia, and decades of harvest pressure, limits the system's ability to absorb that restructuring without lasting change.

6.3 Technological Hazards

The current LED transition is a technological hazard specific to this moment in Norfolk's infrastructure cycle. LED technology has genuine potential for responsible lighting through precise spectral tuning, adaptive dimming controls, and directional shielding, but those capabilities only matter when they are specified in procurement and required at installation. When LED conversion is driven purely by energy cost reduction, the fixtures that get installed are often spectrally harmful, over-bright, and poorly directed — and they are locked into the built environment for fifteen to twenty-five years before the next replacement cycle (Kyba et al. 2017).

The spectral dimension is what makes this moment especially consequential. The high-pressure sodium streetlights that dominated American cities for decades emitted warm orange-yellow light with minimal blue content. The LED fixtures replacing them frequently emit blue-rich white light with correlated color temperatures of 4000K or higher, which is substantially more disruptive to human circadian biology and to the photoreceptive systems of wildlife across taxa (Gaston et al. 2013; Hölker et al. 2010b). The efficiency upgrade is real, but without spectral specification, it aggravates the ecological and health hazards the upgrade is nominally justified by reducing. The procurement decisions Norfolk makes during this replacement window will shape the spectral character of its night environment for a generation.

Societal pressures to chase infinite economic growth deepen this technological hazard. The Jevons paradox describes how improvements in resource efficiency tend to increase total consumption rather than decrease it, because the cheaper a resource becomes the more freely it is used. The paradox was first articulated in the context of nineteenth-century coal consumption, but it maps directly onto the lighting transition: as LED technology has made light cheaper, brighter, and easier to deploy, many cities have responded by illuminating more places more intensely rather than banking the efficiency gains as reduced output. The capitalistic society has normalized expectations for people to work longer hours, including overnight, which drives demand for more light at night in a reinforcing feedback loop. Institutional inertia, if unchecked, will continue to widen the gap between what responsible lighting science recommends and what procurement and regulatory systems actually require.

The global trend toward more ALAN compounds the local picture. Kyba et al. (2017) documented that the artificially lit surface of the Earth is expanding at roughly two percent per year in both radiance and extent, despite widespread LED adoption — the Jevons paradox operating at planetary scale. For Norfolk, it means that even if the city holds its own light output steady, the regional skyglow environment continues to worsen as surrounding municipalities expand their lighting. The light environment experienced by migratory birds, pollinators, and coastal organisms is shaped by a regional and global light landscape that no single city controls, which means local action is necessary but not sufficient, and coordinated regional and state-level policy is essential to any meaningful response.

6.4 Future Hazard Scenarios

Visible Infrared Imaging Radiometer Suite (VIIRS) satellite imaging allows visualization of radiance (measured as watt per steradian per square meter, or W/(sr*m^2)) being emitted. Software created by a third party (Stare, J., 2026) was used to establish hazard scenarios for Norfolk. There are limitations that come with VIIRS imaging because it cannot sense low wavelength light, but for the purpose of this case study it is a sufficient tool to quantify the overall trends of the light pollution in Norfolk. The map in Figure 12 depicts an overlay of varying radiance trends. Areas in green are experiencing dimming, while orange and red areas are brightening. As of 2025, the average radiance inside city limits is approximately 40.2 W/(sr*m^2). From 2012 to 2025, the average trend for radiance within Norfolk city limits shows dimming at a rate of approximately 2.01% per year. Notable hotspots of increasing radiance within the city can be seen in Figure 12, particularly focused around the downtown area, airport, Naval base, and shipbuilding facilities.

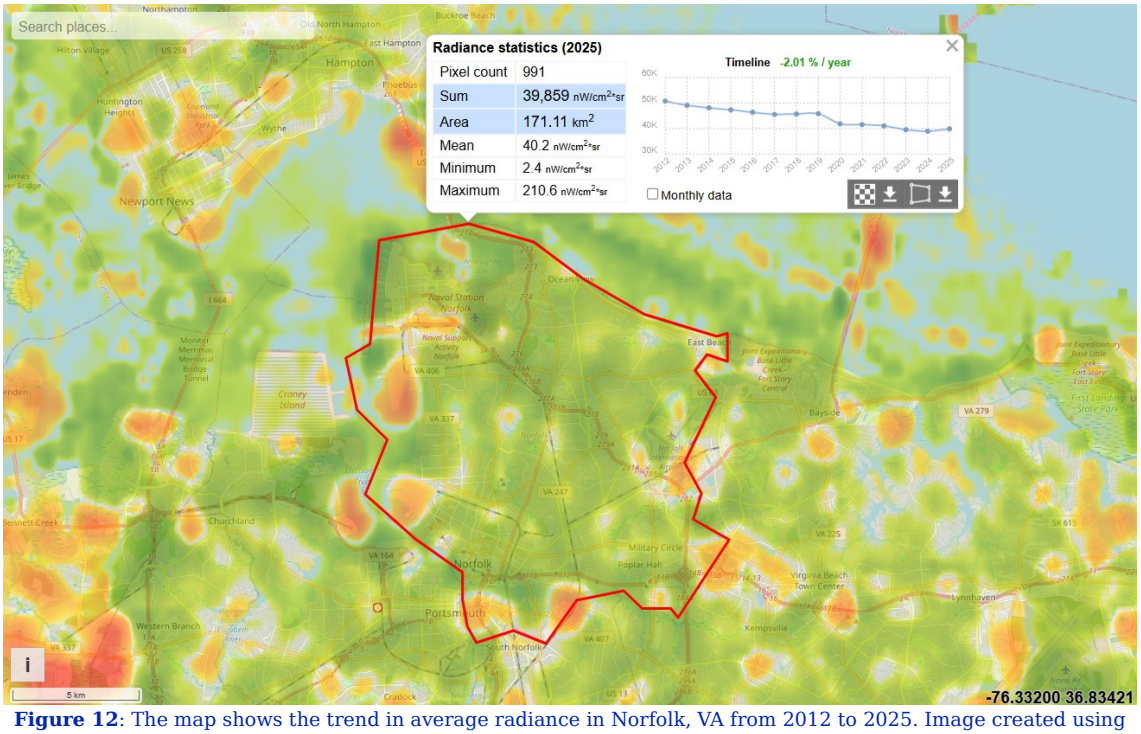

Figure 12: The map shows the trend in average radiance in Norfolk, VA from 2012 to 2025. Image created using lightpollutionmap.info (Stare, J., 2026).

Hazard Scenario 1: Continuation of Current Trends

The graph in Figure 13 shows the projected average radiance in the city over the next 30 years according to the current trend. If radiance in the city continues to follow the same trend, by 2055 average radiance in the city is projected to be 21.8 W/(sr*m^2). While the negative radiance trend is good, the small amount of change, however, is not enough to

eliminate the hazard of ALAN in a timely manner to prevent negative ecological consequences, since there is no known safe amount of light pollution.

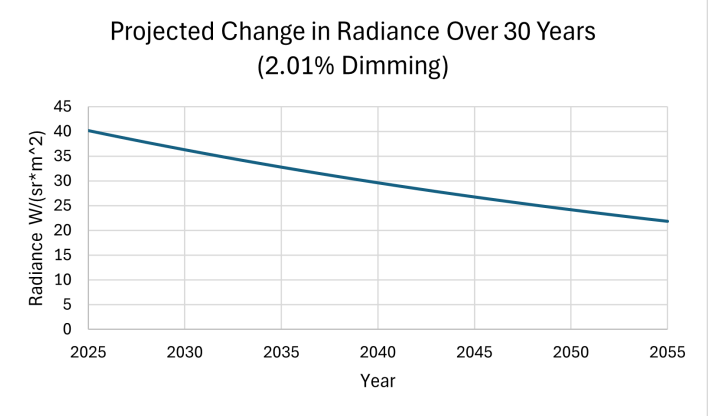

Figure 13: Extrapolating from the most recent average radiance from 2025 and the overall trend of radiance in Norfolk, the graph shows the projected change in radiance for the next 30 years.

Hazard Scenario 2: Decreased Dimming

Hazard scenario two explores the idea that dimming decreases to just 1% per year. In this case, the radiance in 30 years will be approximately 29.7 W/(sr*m^2).

Hazard Scenario 3: Increased Brightening

Hazard scenario 3 supposes that something triggers the trend to go the opposite way. Between the volatile political climate in the United States, the hazardous fractured governance of light, and the newer and more efficient technology available, it is possible for the city to become brighter.

Hazard Scenario 4: Continued Brightening of Hotspots

This hazard scenario accounts for positive radiance trends of hotspots like those noted in Figure 12. Research conducted in Hong Kong found that a relatively small number of highly illuminated buildings were responsible for a disproportionate share of urban light pollution. During events such as Earth Hour, when these buildings reduced lighting, significant decreases in overall brightness were observed (So et al., 2025). In Tucson, Arizona, a large-scale municipal streetlight dimming program resulted in a measurable decrease in skyglow, demonstrating that reductions in ALAN are both achievable and quantifiable (Barentine et al., 2020). Together, these findings reveal a consistent pattern: artificial light is unevenly distributed, strongly shaped by human decisions, and highly responsive to intervention. This reinforces the classification of ALAN as a human-controlled hazard embedded within urban systems.

For coastal cities such as Norfolk, which share characteristics including dense development, port activity, and transportation infrastructure, these global trends provide insight into potential future conditions. Over time, if these hotspots of brightening continue to increase or maintain current brightness, the skyglow will continue to negatively impact the surrounding areas, even if those areas are experiencing dimming. Without proactive management, Norfolk may follow the same trajectory of increasing light pollution and ecological disruption observed in other urban systems.

7
Foresight and Possible Future
Jamie Heffernan, Danielle Delp

7.1 System Exposure, Risk Governance, and Future Trajectories

Artificial light at night(ALAN) exposes Norfolks socio-ecological system to threats due to the hazards are being produced in the system itself. Light pollution is not an outside force like flooding, storm surges, or chemical contamination that arrive and strike exposed assets. ALAN is generated continuuosly by street lights, commercial signage, parking lots, transportation, waterfront development, residential lighting, and other built infrastructure designed to serve human needs. Meaning the system is exposed to threats not because Norfolk is in the path of an external event but because its everyday lighting practices are altering the environmental conditions that wildlife, ecostystems, and human health depend on.

Exposure is caused by both structural and cultural entities. At a local scale, outdoor lighting has been installed to maximize visibility, convenience, mobility, and perceived security, often without equivalent attention to shielding, intensity, timing, spectral composition, or ecological consequence. When in practice this produces skyglow, glare, light trespass, and chronic nighttime illumination across transportation corridors, commercial area, neighborhoods, and waterfront zone. The spread of energy efficient LED technology has intensified this issue in many places because efficiency gains can encourage more lighting rather than better lighting unless policy standards are in place. Norfolk's position within a dense urban coastal region means that local light emissions accumulate across the broader Hampton Roads landscape rather than staying neatly contained within single parcels or districts.

7.1 Scenario Based Futures

Using the hazard scenarios from section 6.4, a spectrum of possible futured was delevoped to explore the future of Norfolk under different circumstances. The spectrum of possible futures in Figure 14 shows how the futures diverge from the current trajectory under different scenarios and what the city might experience by 2055. The first three

scenarios consider little or no mitigation of the current hazards, which puts the system on the path toward an undesirable future. The fourth future scenario consideres what the future may be like under partial mitigation strategies. The final scenario explores a desirable future under the implemetaion of transformative hazard mitigation strategies. Notably, these scenarios do not aim to predict the future, but rather aim to explore plausible futures based on consequences of different actions.

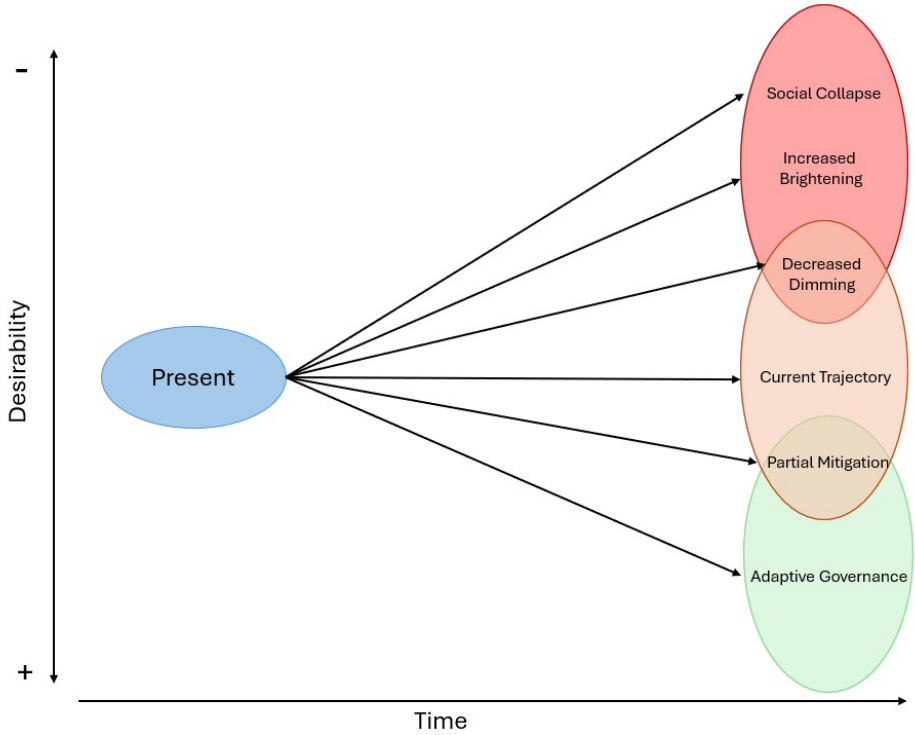

Figure 14: The spectrum of possible futures speculates what the future may be like under different scenarios. Across the spectrum, futures in red are less desirable, and futures in green are more desirable.

7.1.1 Social Collapse

If Norfolk experiences some kind of natural disaster, radical social reform, power grid failure, or energy crisis, this could lead to a future with no light at night. If light were for whatever reason completely banned at night, all human activity would be limited to daylight hours, which would stress the economy as working hours would be limited in the winter. First responders would have difficulty responding to emergencies, it would be unsafe for people with visual disabilities to be out at night, and traveling the roadways would come with higher risk. While more light does not mean less crime overall, the complete absence of light at night may change crime dynamics in the city. During prolonged streetlight outages, the number of crimes committed do not increase, but the location of the crime tends to shift closer to the area of outage (Chafin et al., 2021). In the total absence of light, the distribution of crimes in the city may change. Access to light at night has allowed humanity to flourish, and some amount of light at night is necessary for modern society to function. While this would benefit the natural ecosystem, this future would likely cause local economic collapse, social restructuring, and be dangerous to citizens.

7.1.2 Increased Brightening

In a future where brightening increases through a lack of cohesive governance and limitations, Norfolk could experience a future with bright, 24 hour light. With no regulations on lighting curfews, and ligthing upgrades that introduce brighter and whiter light, the city sees a change from the current dimming trajectory to a brightening trajectory, and the city experiences a brightly lit night. In this undesirable future, biodiversity would be low and residents would expereince poor health and wellbeing. The region would be devoid of nocturnal pollinators, and local agrculture would suffer. Home gardeners would be primarilty limited to self pollinating plants. The disparate injustice expereinced by those in disadvantaged and impoverished communities would be very high, as access to adequate healthcare is easier for those in privelaged positions. Expereincing a dark sky would also become a privilege, accessable only to those who have the ability to travel to dark sky areas outside the city.

7.1.3 Decreased Dimming

In this scenario, current lighting practices continue with only piecemeal upgrades driven by cost, convenience, or short term safety concerns. In this future, LED conversions proceed without strong standards for shielding, brightness, color temperature, or timing, and hotspots noted in section 6.4 get brighter from lack of regulation. In a situation where dimming decreases or stagnates at 0% per year, skyglow persists, bird collision risk remains high during migration, insect and bat habitat quality declines, and human sleep disruption persists in densely lit neighborhoods. The city would likely still experience the same consequences as in scenario 7.1.1.

7.1.4 No Action

The difference between the decreased dimming scenario and the continuation of the current trajectory is minimal. Even if the city continues to see an average dimming of 2% per year, it is not enough to put the system on the path toward a desirable future. There are economic benefits as more efficient LEDs replace current infrastructure, but health and wildlife still suffer the consequences of a bright night. Under this scenario, the system becomes more efficient in energy

terms but not more resilient in ecological or public health terms. The long term consequences of no action are cumulative and difficult to reverse: chronic biodiversity loss, weakened ecosystem services, greater social inequity, continued cultural loss of the night sky, and a governance pattern that normalizes light pollution.

7.1.5 Partial mitigation

In this scenario, Norfolk adopts some responsible lighting practices in selected sectors such as municipal facilities, public outreach campaigns, and voluntary bird migration measures, but it does not establish a fully integrated citywide framework. This scenario would likely reduce some localized harm, especially during peak migration or in highly visible public sites, but the gains would remain uneven. Some neighborhoods or institutions would improve while commercial corridors, private properties, and transportation zones continued to generate diffuse light pollution. This future is better than no action, but it still leaves the system fragmented and dependent on voluntary compliance.

7.1.6 Adaptive Governance

In the desirable adaptive governance scenario, Norfolk treats lighting as infrastructure that must serve safety and function while also protecting human health, wildlife, and dark sky conditions. Municipal standards align with responsible lighting principles, including full shielding, warm color temperatures, lower intensity, adaptive controls, and curfews where appropriate. Lighting decisions are integrated into planning, zoning, public works, redevelopment, and coastal resilience efforts. Migratory bird protection would be strengthened through regular participation in Lights Out campaigns and building level operational changes during migration windows. Utilities and city departments would expand access to low impact lighting options, which the City of Norfolk is already supporting in its 2026 legislative agenda (City of Norfolk, 2026). This is the most resilient future because it reduces harm at the source rather than merely reacting to isolated symptoms.

7.2 Prognosis

Several future challenges can be expected if radical change is not made. First, Norfolk will likely experience continued tension between lighting expansion and ecological protection as redevelopment, transportation upgrades, and waterfront activity increase nighttime illumination. Second, climate adaptation and coastal infrastructure investment may unintentionally add new lighting unless responsible standards are built into resilience planning from the beginning. Third, the cumulative effects of ALAN may become more visible in already stressed ecosystems, especially where habitat loss, water quality degradation, and fragmentation have already reduced ecological redundancy. Fourth, equity concerns may sharpen if lower income communities continue to bear disproportionate exposure to intrusive or poorly managed nighttime lighting while having limited influence over the decisions that shape those exposures.

Both local and global processes are shaping the system's trajectory. Locally, Norfolk's built form, land use patterns, airport activity, roadway lighting, port and waterfront infrastructure, redevelopment, and neighborhood level fixture choices determine where and how intense exposure occurs. Globally, broader trends such as urbanization, falling LED costs, expanding nighttime economies, and the worldwide growth of artificially lit areas increase pressure toward more lighting unless countered by policy. Research and advocacy organizations continue to document these global trends, while local institutions determine whether Norfolk amplifies or resists them through its own governance choices. Norfolk's lighting system is currently on a contested trajectory: without stronger governance, ALAN will continue to erode ecological function, human well being, and dark sky access, but with coordinated responsible lighting policies, the city has a realistic path toward a safer, healthier, and more resilient nighttime environment.

The system prognosis is mixed but it is not hopeless, Norfolk is not locked into a single future. The prognosis depends on whether the city continues to treat nighttime lighting primarily as a visibility tool or begins governing it as a socio ecological issue with real consequences for wildlife, health, and quality of life. The presence of regional migration campaigns, the spread of responsible lighting principles, and Norfolk's recent support for lower impact lighting options all suggest that a transition toward more intentional governance is possible. Without enforceable standards and cross sector coordination however, current efforts may remain too limited to offset the broader trend toward increasing urban illumination.

7.3 Emerging Outcomes

Some steps have already been taken to move the system toward a more desirable future. Regionally, Bird Safe Hampton Roads and partner organizations have established Lights Out campaigns to reduce migratory bird collisions by encouraging buildings and residents to turn off unnecessary lights during migration season. The National Audubon Scoiety (2026) lists Norfolk's Lights Out Hampton Roads effort among existing bird safe programs, indicating that this is part of a recognized migration protection strategy rather than a one off event. At the policy level, Norfolk's 2026 legislative agenda supports obtaining additional low light impact outdoor lighting options from utilities to reduce unintended illumination and maintain dark skies. At the broader guidance level, responsible lighting standards are now clearly articulated through DarkSky International and allied professional organizations, giving local governments a practical model for future code and infrastructure changes (DarkSky International, 2024).

The current regional campaigns and policy language show growing recognition of the problem, which is an important first outcome because wicked problems cannot be addressed until stakeholders acknowledge that the hazard exists and requires coordination. Norfolk's inclusion of low impact lighting in its legislative priorities is also a sign that dark sky protection is moving from advocacy language into governmental framing. Even so, the outcomes should be understood as preliminary. Awareness has increased, and some pathways for action are now visible, but the city has not yet fully institutionalized a comprehensive responsible lighting regime. In other words, the system has started to pivot, but it has not completed the turn.

8

Risk Assessments

Danielle Delp, Jamie Heffernan

Artificial light at night (ALAN) is a continuous, internally generated hazard within Norfolk's socio ecological system. Unlike external hazards such as flooding or storm surge, ALAN is produced daily through built infrastructure including street lighting, commercial development, transportation corridors, and residential sources. This means exposure is constant rather than episodic, creating long term environmental pressure on ecosystems and human systems. Because the hazard is embedded in normal urban function, it is often overlooked in traditional risk frameworks despite its

cumulative impacts.

The systems most at risk from ALAN in Norfolk include nocturnal wildlife, migratory bird populations, and human communities exposed to persistent nighttime lighting. Norfolk lies within the Atlantic Flyway, making migratory birds particularly vulnerable to disorientation and collision due to illuminated urban areas (Longcore & Rich, 2004). In addition, insects and other nocturnal species experience disrupted behavior and habitat loss, which can reduce ecosystem stability (Hölker et al., 2010). Human receptors are also affected, especially in densely developed neighborhoods where intrusive lighting can disrupt sleep cycles and reduce quality of life (Hölker et al., 2010).

At the same time, there is risk associated with too little ALAN. Light is an asset to human communities, allowing freedom to extend daily activities into the night. There is risk associated with decreased visibility in terms of vehicle collisions and for the prevention of falls. Crime and its distribution are also somewhat tied to the amount of light.

8.1 Scenario Based Risk Assessment

Risk in Norfolk's ALAN system is assessed using the relationship:Risk=P(Hazard)×Fragility×Value.

In this case, the hazard is ALAN, fragility is the system's sensitivity to light exposure, and value represents the ecological, human, and social importance of the affected systems. This framework allows risk to be compared across different future scenarios rather than treated as a single static condition.

8.1.1 Ecosystem Health

In possible futures 7.1.2-7.1.4, there is a high probability that light pollution persists. Evidence shows that the ecosystem is highly sensitive to light exposure. The value of biodiversity and ecosystem services is extremely high, especially considering the inverse relationship between nighttime pollination by insects and ALAN (Knop et al., 2017). Considering this, there is high risk to ecosystems in a scenario with high ALAN.

8.1.2 Human Health

Similarly, the risk to human health is also high under the same circumstance as in section 8.1.1. Human health is also highly sensitive to light, and the value of health is high. The diseases associated with light exposure (cancer, diabetes, cardiovascular disease) are among the top ten causes of death in the United States, according to the Center for Disease Control (2026). This creates a high risk to the human population. In low socioeconomic communities, this risk is even greater when accounting for the lack of accessability to healthcare.

8.1.3 Safety

In terms of safety, the risk in this scenario is tied to darkness. Unless the system undergoes a total collapse like in section 7.1.1, it is unlikely experience total darkness. The response of the system to lack of light is moderate. While the safety associated with utilitarian uses of light such as being able to see where one is walking or driving are high, the response of criminal activity in low light situations is low. Crime has not been found to increase in areas of darkness (Chafin et al., 2021). The value of safety in the community is high. There is greater risk to the visually impaired in low light scenarios who could be injured by an accident, and different crimes can potentially high impacts in the community. Across all of these factors, this makes the risky to safety moderate in a scenario of increased darkness.

Figure 16 Summarizes this risk assessment, showing how hazard, probability, system fragility, and the value of exposed assets combine to weigh the risk of different scenarios for exposed assets.

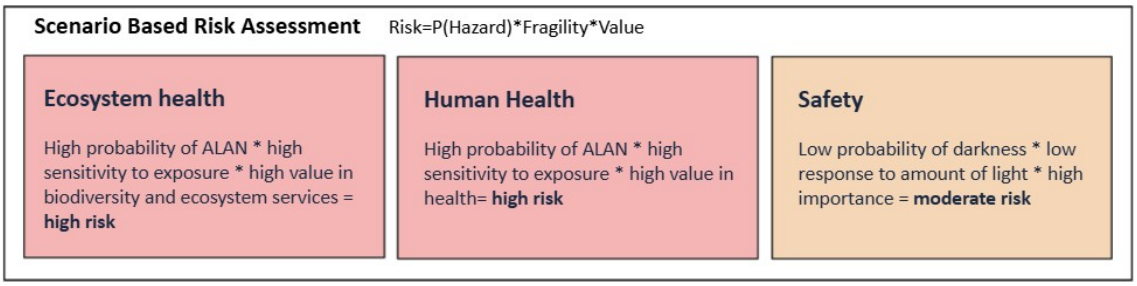

Figure 16: The risk assessment analyzes the risk to different assests. The risks can be compared to one another in this figure.

8.2 Risk Implications for Interventions

The differences in risk across the future scenarios show that the most important factor shaping outcomes in Norfolk is how lighting is managed. In scenarios where hazard probability remains high and fragility is not reduced, risk continues to build over time, especially for already stressed ecosystems and communities. This suggests that simply maintaining current practices or making small improvements is not enough to meaningfully reduce impacts.

Instead, the most effective approaches are those that reduce unnecessary lighting at the source while also addressing how sensitive the system is to exposure. This includes improving lighting design, limiting excessive brightness and duration, and better aligning lighting decisions across sectors. At the same time, protecting high value systems such as migratory bird pathways, nocturnal habitats, and residential areas can help reduce the overall vulnerability of the system.

Looking across the scenarios, the shift toward coordinated and intentional lighting practices stands out as the key difference between higher and lower risk futures. When considering interventions and future trajectories, the trade offs between more and less light have to be weighed against one another. This highlights that reducing ALAN impacts in Norfolk is less about adding more technology and more about changing how lighting is planned, used, and governed over time.

9 Transformation Knowledge: Assessing Interventions

Abby Lahey, Jamie Heffernan, Danielle Delp

9.0 Considering the Interventions

Outdoor lighting in Norfolk is currently treated as a commodity that property owners and businesses purchase and emit at will, while darkness is treated as the absence of that commodity rather than a shared resource with its own ecological and human function. A billboard owner takes the night sky over a neighborhood. A retailer with an unshielded floodlight takes it over a residential block. Emitters do not pay for what they consume from the commons, and the residents and ecosystems downstream bear the costs (Gaston et al. 2013; Kyba et al. 2017). Light at night cuts through infrastructure, governance, public health, ecology, economy, and the cultural relationships people have with the night itself (Hölker et al. 2010a).

The interventions below begin from the premise that darkness is infrastructure, comparable to clean water or quiet air, and they extend the work CRL and DarkSky International have already done in the region, including the recommendations of *Dark and Quiet Skies II for Science and Society* (Walker et al. 2021). Effective governance of diffuse pollutants has historically required structural backing in measurement, governance, funding, and enforcement (Levin et al. 2012).

Two conditions shape what Norfolk can do. The LED transition window is closing now. Fixtures installed during current replacement cycles will remain for decades, and many U.S. cities have already locked in high-CCT, blue-rich lighting despite warmer alternatives that reduce ecological and health impacts at comparable energy savings (U.S. Department of Energy 2023; Falcón et al. 2020). Dominion Energy is the second condition. As a state-regulated investor-owned utility whose revenue depends on its rate base, Dominion's financial incentives oppose any reduction in fixture count or output, which makes the company structural opposition rather than a stakeholder to coordinate with (Costello 2018).

Satellite constellations have raised global sky brightness roughly ten percent above natural levels (Falchi et al. 2023) and threaten Indigenous star-knowledge traditions that depend on dark-sky access (Hamacher and Norris 2011). Orbital infrastructure is beyond municipal authority, and the local work below becomes more important as that contribution continues to grow. The interventions are largely Discipline-quadrant work, with Transformation moves where the architecture allows, designed for the legal authority and political conditions Norfolk actually has rather than the conditions a fully transformative response would require.

9.1 Norfolk's Authority Over Its Nighttime Environment

Norfolk's first intervention establishes regulatory authority, institutional capacity, monitoring infrastructure, and a first designated zone as one coordinated move. Each piece is required to make the others work. The Lightshed Framework is source-attributed and propagation-aware. A high-mast fixture at the Port of Virginia does not stop at the waterfront. Light reflects off the Elizabeth River, scatters through coastal humidity, and reaches migratory birds on the Atlantic Flyway, estuarine species whose behavioral cycles depend on natural darkness, and residential neighborhoods kilometers from the source (Davies and Smyth 2018; Manfrin et al. 2017).

The framework identifies major source clusters, models propagation across coastal air and water, and sets baseline emissions and propagation budgets the city can enforce against. Bortle classification gives the public a tracking tool. Norfolk's residential outskirts currently sit in Class 6 or 7, with downtown and waterfront higher (CRL 2024), and a fifteen-year reduction of one or two classes is communicable and measurable.

The Norfolk Night Council holds the authority. Its composition uses proportional voting weight tied to exposure burden, so residents of historically redlined and currently most-exposed neighborhoods hold proportionally greater voice than parties whose role is operational or commercial. The design responds directly to a standard failure mode of environmental governance, which tends toward capture by the largest operational stakeholders unless voting structure prevents it (Walker et al. 2013).

The Council houses a Lightshed Authority with trained inspectors, a public complaint portal, and authority to issue warnings, fines, and abatement orders. ODU and EVMS partnerships generate Norfolk-specific research on health, ecological, and equity dimensions of ALAN exposure, a public dashboard makes propagation data visible to residents in real time, and a community science arm trains residents to contribute observations using lux meters, sky-quality meters, and structured sleep diaries.

The Dark Harbor designation makes the Elizabeth River harbor the first regulated zone, because water reflects and transmits artificial light farther than land-based propagation, affecting estuarine species, migratory bird navigation, and Chesapeake Bay aquatic ecosystems (Bolton et al. 2017; Davies and Smyth 2018). The designation prohibits upward-facing fixtures within the reserve, requires shielded amber and red-spectrum lighting, and retrofits port and industrial floodlighting on a defined timeline. Norfolk Naval Base falls partially under federal jurisdiction and is addressed through coordination rather than direct regulation, with the limitation noted in 9.10.

Pros:

- Authority, capacity, and evidence base in one coordinated move.
- Aligns with watershed and shoreline logic Norfolk already uses.
- Bortle classification gives the public an accessible tracking tool.
- Proportional voting responds to documented governance-capture risk.
- The research program addresses the meta-fragility of low local evidence.

Cons:

- Substantial up-front cost.
- Monitoring infrastructure must be built where it does not yet exist.
- Propagation modeling carries methodological uncertainty.
- Source-attributed regulatory logic is new for stakeholders.
- Voting structure will face resistance from established interests.

SDGs: 11, 14, 15, 16, 17.

9.2 Recognizing ALAN as a Pollutant

Norfolk has no legal category that matches what artificial light at night actually is. The EPA maintains established criteria for nutrient, air, and water pollution. Light has none, despite meeting the operative definition of pollution as something that makes an environment unsuitable or unsafe for use (Merriam-Webster 2026). Designating ALAN a pollutant moves it out of the nuisance regime, where harm has to be demonstrated case by case, and into the threshold regime, where exceeding measurable limits is the violation.

The shift moves the burden of proof from affected residents to emitters and opens legal standing for residents in historically over-exposed neighborhoods to bring civil rights claims under Title VI, on the same disparate-impact logic used for air and water pollution (Bullard 2008). Norfolk's municipal code establishes the framework first. Virginia state enabling legislation is pursued in parallel, because the Dillon Rule otherwise constrains what the city can enforce (Werner 2018). Federal EPA recognition operates on the longest horizon.

The regulatory framework will tighten over fifteen to twenty-five years. It is not a deferral. Every diffuse pollutant in U.S. regulatory history has followed a comparable arc from initial classification to comprehensive restriction (Werner 2018; Brandt 2007).

Phase 1 (years 1–5): Shielding required for all new fixtures; CCT capped at 3000K residential, 2700K coastal and ecological zones, 2200K within Dark Harbor (DarkSky International 2020); 11pm–6am curfews on advertising and decorative facade lighting with exemptions; Lights Out Hampton Roads codified into law during peak migration (Van Doren et al. 2017).

Phase 2 (years 5–15): Existing fixtures brought into compliance; brightness caps per district; expanded curfews; tighter coastal buffers.

Phase 3 (years 15–25): Non-essential outdoor lighting prohibited, including illuminated commercial advertising.

The First Amendment commercial speech doctrine constrains how the prohibition can be structured, since regulations must satisfy intermediate scrutiny under *Central Hudson Gas & Electric Corp. v. Public Service Commission of New York* (1980). Time-place-manner restrictions framed around public health and environmental protection are more likely to survive, and the phased structure builds the required evidentiary record.

The liability shield addresses a structural driver of over-lighting. Property owners often over-light due to insurance and legal advice, where dim lighting is treated as negligence regardless of actual causation (Pauley 2004). Property owners who comply with city standards are protected from negligence claims based on dim lighting alone, similar to Virginia shoreline-restoration liability protections (Virginia Code § 28.2-1100 et seq.).

Pros:

- Establishes the legal category needed for all other interventions.
- Strong historical precedent supports phased regulation.
- Opens Title VI environmental justice pathways.
- Liability shield removes a major driver of over-lighting.
- Early phases deliver immediate benefits.

Cons:

- Political resistance from multiple industries.
- Dillon Rule constraints without state support.
- Phase 3 faces constitutional challenges.
- Long timeline risks loss of political continuity.

SDGs: 3, 11, 13, 16.

9.3 Adaptive Spectrum and Shielding Retrofit Program

The largest source of Norfolk's nighttime light is the lighting already installed: streetlights, parking-lot floods, building uplights, illuminated signage, and port high-mast floods. Once an LED is installed it stays there for fifteen to twenty years (U.S. Department of Energy 2023), and the retrofit window is closing now.

Track 1 puts a clip-on shield on every unshielded outdoor fixture in the city, redirecting light toward the surface it was installed to illuminate rather than across property lines or upward (DarkSky International 2020). Per-unit cost sits in the tens of dollars. Cost cannot be the argument against moving.

Track 2 phases in color-tunable warm-spectrum LEDs through normal replacement cycles, capped at 2700K in residential zones and 2200K in coastal and ecologically sensitive zones, dimming after eleven and defaulting off between two and dawn with motion override. Insect attraction, pollinator disorientation, fish behavioral disruption, and human melatonin suppression all scale with the short-wavelength end of the spectrum (Falcón et al. 2020; Knop et al. 2017), and standard high-CCT LEDs raise blue emissions even where total energy falls (Kyba et al. 2017). Color-tunable warm-spectrum LEDs solve the whole problem where standard warm LEDs solve half.

Funding comes from a corporate light-pollution levy structured as a cap on permitted output. A Pigouvian tax would price the externality and let the activity continue, treating darkness as something wealthy emitters can buy out of (Bullard 2008). A cap with penalties for exceedance treats darkness as a commons whose limits are non-negotiable.

Major emitters above a defined baseline (port floods, big-box parking lots, stadium arrays, refinery floods, illuminated billboards) face an enforceable lumen-output cap measured at the source, and violation fees flow into a polluter-pays mitigation fund. Allocation tracks exposure burden directly. Historically redlined corridors east of downtown carry higher ambient streetlight density and more commercial signage exposure, and retrofits go there first, not to the geography of existing municipal capital spending, which has historically run in the opposite direction (Gaston et al. 2013). Anti-pass-through provisions block recovery through tenant rent or consumer prices.

Pros:

- Addresses Norfolk's largest existing ALAN source.

- Track 1 produces measurable reductions within months while Track 2 matures over time.
- Motion-activated operation with emergency override addresses safety concerns.
- The cap redirects costs from residents to major emitters.
- Allocation embeds equity into the funding structure.

Cons:

- Dominion Energy coordination is unresolved here and addressed in 9.4.
- Risk of vendor lock-in for warm-spectrum LED supply.
- Emitters will likely challenge the cap methodology legally and politically.
- Dillon Rule constraints may limit enforcement without state legislation.

SDGs: 7, 11, 13, 14, 15.

9.4 Public Ownership of Streetlight Infrastructure

Norfolk's streetlights belong to Dominion Energy, and the city pays for service under a State Corporation Commission-approved Schedule SL tariff (Virginia Electric and Power Company 2024). Every change to fixture type, output, or schedule routes through an SCC tariff modification with an eighteen-month floor. Dominion's revenue depends on its rate base, fixture count and output sit inside that rate base, and the entity Norfolk has to negotiate with has a financial incentive to preserve the lighting Norfolk is trying to reduce (Costello 2018). Every other intervention in this section passes through that contradiction. Bringing streetlight assets onto the city's books removes it.

Sacramento Municipal Utility District, Los Angeles Department of Water and Power, and Seattle City Light show that public ownership of electrical infrastructure is operationally tractable at U.S. urban scale, though all three sit in home-rule states without Virginia's Dillon Rule. Norfolk's path is narrower. Full municipalization requires state enabling legislation and a negotiated buyout the SCC has institutional history of deferring to Dominion on. A multi-municipal coalition with other Virginia cities pursuing similar reforms shifts the legislative arithmetic in Richmond, where one city's request reads as a Dominion problem and a regional coalition reads as a political problem. SCC reform advocacy attaches to that same pathway. This is the section's transformation move. Dominion will fight in Richmond, at the SCC, and in court, and the political coalition will need to outlast that fight. Without it, the section accepts a permanent lighting partner whose financial structure opposes everything else proposed.

Pros:

- Removes the structural opposition every other intervention in this section has to negotiate around.
- Takes streetlight assets out of Schedule SL tariff logic and aligns ownership with the entity bearing the costs of over-lighting.
- Multi-municipal coalition creates co-benefits for energy democracy and rate reform across Virginia.
- Preserves a transformation pathway in a section otherwise sitting in the discipline quadrant.

Cons:

- Lowest feasibility and highest political cost in this section.
- Dillon Rule requires state enabling legislation, and the SCC has institutional history of deferring to Dominion.
- No Virginia public power precedent at scale, and existing U.S. precedents sit in home-rule states.
- Substantial up-front asset acquisition cost.
- Multi-decade horizon risks loss of political will across municipal administrations.
- Partial municipalization could leave Norfolk operationally worse off than the current arrangement.

SDGs: 7, 11, 16, 17.

9.5 Strategic De-Illumination

The first four interventions in this section refine existing capacity. This one removes it. A citywide audit identifies redundant and excessive fixtures across Norfolk, with a phased removal target of twenty percent of poles in over-lit corridors by 2040. The premise is that the cheapest, most effective, and most ecologically defensible response to over-lighting is to take it down. LED efficiency gains have not produced reduced output across global cities. They have produced more lighting at lower per-unit cost, brighter fixtures, longer hours, and expanded coverage (Kyba et al. 2017). Refinement programs that swap fixture for fixture reduce per-fixture impact while leaving the underlying capacity in place. Removal interrupts that dynamic. At conversion sites, options range from restored darkness to native plantings to distributed energy generation on retained grid connections, and replacement is secondary. Some sites simply become darker.

Pole count is the implementation lever. The actual goal is lumen reduction in defined zones, with poles as one mechanism among several, since parking-lot floods, building-mounted fixtures, and high-mast lighting often sit outside standard streetlight pole counts.

Safety is the contested terrain. Each conversion site is compared against statistically matched control sites over multi-year windows for safety incidents, traffic outcomes, and biodiversity indicators. Incident-driven thresholds, the structure that pauses a program after a single high-profile event near a converted site, convert any policing or media event into a program-killer regardless of whether the conversion played any causal role. Statistical comparison is the only defensible methodology for a program whose premise contradicts the unstated assumption that more light is always safer.

Pros:

- Removes capacity rather than refining it, addressing the Jevons dynamic that has absorbed every prior efficiency gain in Norfolk's lighting trajectory.
- Reduces ongoing operational and maintenance costs.
- Produces measurable lumen and skyglow reductions in converted zones.
- Complements the retrofit work in 9.3 by removing what would otherwise be retrofitted.
- Builds a visible cultural commitment to intentional darkness.

Cons:

- Public safety perception is the dominant political risk and will be tested with every incident anywhere near a converted corridor.
- Pole removal logistics require Dominion coordination on grid disconnects, and Dominion is under no obligation to expedite.
- The twenty-percent-of-poles target can be technically satisfied without addressing the high-mast, parking-lot, and building-mounted lighting that produce most of the actual lumens.
- Maintenance liability for replacement structures becomes its own political fight if responsibility is unclear.
- No U.S. city has implemented citywide de-illumination as a flagship, so Norfolk would be operating without close municipal precedent.

SDGs: 11, 13, 15.

9.6 Supporting Interventions

These supporting interventions complement the flagships in 9.1 through 9.5. They are organized by the five Essential Transformation Variable (ETV) groups used throughout this report: Infrastructure and Built Environment, Governance and Policy, People/Culture/Community, Economic, and Earth's Life-Support System. The ETV grouping ties each item to the dimension of the system it acts on. None of these require the institutional restructuring the flagships demand, but each strengthens the overall response.

9.6.1 Infrastructure and Built Environment

- Bird-safe building treatments and window patterning (visible markers on glass surfaces that disrupt the reflective illusion driving collisions) on high-collision waterfront and downtown structures, prioritized for peak Atlantic Flyway migration windows (Van Doren et al. 2021).
- Vegetated light buffers along the waterfront, implemented through existing tree-canopy and shoreline-restoration programs.

9.6.2 Governance and Policy

- Lighting standards code reform: maximum-as-well-as-minimum illumination thresholds, with data justification required for new installations above baseline.
- Health Impact Assessments for major lighting projects, structured within existing zoning-conditions authority.
- Combined pollution mapping in zoning decisions, layering ALAN exposure with air, water, and noise burden to surface cumulative impact.
- Private right of action for light trespass, pursued through state-level advocacy in Richmond, since Virginia localities cannot create new private causes of action under the Dillon Rule.
- Litigation pathways under existing nuisance and zoning law, with settlement frameworks structured to require retrofit of offending fixtures rather than monetary damages alone.
- Voluntary ALAN design codes for the waterfront business district as a bridge to the mandatory standards in 9.2 Phase 2.
- Operational curfews for advertising and decorative lighting between 11pm and 6am, with exceptions for navigation, emergency, and specifically authorized uses.

9.6.3 People, Culture, and Community

- Earth Hour participation and Norfolk Sky-Quiet Hours tied to migration windows and seasonal celestial events.
- Norfolk Dark-Sky Tourism on the Waterfront, modeled on Lincoln City, Oregon's coastal dark-sky designation.
- Indigenous Astronomy Partnership, scoped honestly as a multi-year relationship-building commitment with Virginia tribes (Pamunkey, Mattaponi, Nansemond, Chickahominy) under formal MOU rather than a planning bullet.
- ALAN literacy in school curricula, framed as civic education on environmental governance, not personal mitigation training.
- Community decision authority over lighting projects: voting members on the Norfolk Night Council from most-exposed neighborhoods, budget control over the polluter-pays mitigation fund, and veto authority over major lighting installations in their districts.

9.6.4 Economic

- Fiscal framing for the full program: Medicaid savings from reduced sleep-disorder and circadian-disruption morbidity, energy savings from reduced output, avoided liability under the 9.2 shield, and reduced municipal operational costs.
- Reduction-incentive lighting contracts: vendors paid on outcomes (lumens reduced, energy saved, compliance with standards) rather than fixtures installed.
- Polluter-pays mitigation fund directed to highest-exposure neighborhoods first, with allocation tied to measured exposure.
- Subsidies and rebates with honest framing distinguishing existing federal policy from new municipal supplement.
- Removal of utility tariff structures that reward over-lighting, addressed through SCC advocacy in parallel with 9.4.
- Extended Producer Responsibility for outdoor lighting manufacturers: holding manufacturers financially accountable for end-of-life management of LED fixtures, including rare-earth recovery, electronic waste handling, and hazardous-component disposal.

9.6.5 Earth's Life-Support System

- Moon and tide-responsive waterfront lighting: fixtures that adjust output based on lunar phase and tidal cycle to align nighttime illumination with natural ambient light, piloted at small scale before any citywide deployment given current implementation maturity.
- Bird migration response dimming during peak Atlantic Flyway passage, triggered by weather radar data on real-

time bird density (Van Doren et al. 2021).

- Coastal dark corridors along the Atlantic Flyway: linked stretches of low-emission shoreline forming a continuous low-light flight path for migrating birds, anchored on the Dark Harbor in 9.1 and extended along adjacent shoreline.
- Baseline ecological monitoring tied to key indicator species: menhaden, blue crab, dog whelks, and migratory bird strike data.

9.7 Patterns and Limitations

The flagships build on each other in a deliberate order. 9.1 establishes regulatory authority, monitoring infrastructure, and the first designated zone, creating the institutional capacity the rest of the section depends on. 9.2 creates the legal category that gives 9.1's authority enforceable thresholds and opens civil-rights pathways for affected residents. 9.3 deploys the retrofit and funding mechanism that 9.1's monitoring measures and 9.2's standards govern. 9.4 confronts the structural opposition embedded in the regulated investor-owned utility model that all prior interventions have to negotiate around. 9.5 subtracts capacity rather than refining it, addressing the Jevons dynamic that absorbs every prior efficiency gain. Each step is more politically demanding than the last. The order tracks what becomes possible once the previous step is in place. The full comparative summary appears in Figure 15.

Table N. Section 9 Intervention Matrix

Comparative summary of flagship interventions (9.1–9.5) and supporting intervention groups (9.6.1–9.6.5) across pillar, time horizon, key tradeoffs, adaptive trigger, and SDG alignment.

Intervention	Pillar(s)	Horizon	Key Pros	Key Cons	Adaptive Trigger	SDGs
9.1 Norfolk's Authority Over Its Nighttime Environment	GOV, INF, PPL	S–M	Foundational authority and evidence base; exposure-burden voting; Bortle tracking accessible to public	Substantial up-front cost; propagation modeling uncertainty; novel framework for stakeholders	Propagation exceeds modeled baseline by >15% in any zone → revisit fixture standards in zone	11, 14, 15, 16, 17
9.2 Declaring Light a Pollutant and Phasing It Out	GOV, PPL	S–L	Legal category every other intervention depends on; Title VI standing; liability shield removes over-lighting driver	Dillon Rule risk; Central Hudson challenge in Phase 3; political will across administrations	State enabling legislation not passed within 5 years → adjust implementation pathway	3, 11, 13, 16
9.3 Adaptive Spectrum and Shielding Retrofit	INF, ECO, GOV, ELSS	S–M	Addresses Norfolk's largest existing ALAN source; fast-acting Track 1; equity built into allocation formula	Dominion coordination unresolved; single-vendor lock-in risk; cap-based levy faces Dillon Rule	Shielding compliance below 80% in any district → escalate enforcement	7, 11, 13, 14, 15
9.4 Public Ownership of Streetlight Infrastructure	GOV, ECO, INF	L	Removes structural opposition embedded in IOU rate base; aligns ownership with cost-bearer; preserves transformation pathway	Lowest feasibility in section; Dillon Rule and SCC deference; no Virginia public power precedent at scale	Multi-municipal coalition reaches threshold of participating cities → state legislative push	7, 11, 16, 17
9.5 Strategic De-Illumination	INF, ELSS, ECO	S–M	Interrupts Jevons dynamic by removing capacity; operational cost reduction; ecological co-benefits at conversion sites	Safety perception political risk; no U.S. flagship precedent; pole-count metonymy gaming	Statistically significant safety differential at conversion sites vs. control sites → pause and assess	11, 13, 15
9.6.1 Infrastructure & Built Environment (supporting)	INF, ELSS	S–M	Targeted high-collision interventions; bridges existing tree-canopy and shoreline programs	Scope-limited; does not address total lighting load	Bird strike data exceeds threshold at monitored buildings → expand mandatory treatments	11, 15
9.6.2 Governance & Policy (supporting)	GOV	S–M	Operationalizes flagships through existing zoning and code authority	Private right of action requires state action; voluntary measures have limited durability	Voluntary compliance below threshold → move to mandatory standards	11, 16
9.6.3 People, Culture & Community (supporting)	PPL	S–L	Builds political coalition; civic education; community decision authority over highest-exposure neighborhoods	Indigenous Astronomy Partnership requires multi-year relationship-building, not bullet-point implementation	Community participation on Night Council below proportional representation → governance review	4, 11, 16, 17
9.6.4 Economic (supporting)	ECO	S–M	Outcome-based contracts shift vendor incentives; EPR addresses end-of-life manufacturer responsibility	Tariff structure removal requires SCC; subsidy framing depends on federal policy environment	Contract outcomes below committed lumen and energy reductions → contract restructuring	7, 8, 11, 12
9.6.5 Earth's Life-Support System (supporting)	ELSS	S–L	Direct ecological responsiveness; baseline monitoring informs all flagships	Lunar/tidal lighting still maturing; coastal dark corridors require multi-jurisdictional coordination	Indicator species data shows continued decline despite intervention rollout → escalate spectrum and shielding restrictions	11, 14, 15

Legend

Pillar codes: INF = Infrastructure & Built Environment; GOV = Governance & Policy; ECO = Economic; ELSS = Earth's Life-Support System; PPL = People, Culture & Community.

Time horizon codes: S = Short-term (0–5 years); M = Mid-term (5–15 years); L = Long-term (15+ years).

Adaptive trigger format: observed condition → policy response. Triggers are designed to drive specific corrective action, not to function as automatic kill-switches.

Figure 15: Figure 15. Comparative summary of Section 9 interventions across pillar, time horizon, key tradeoffs, adaptive trigger, and SDG alignment. Rows cover the five flagship interventions (9.1–9.5) and the five supporting intervention groups organized by ETV (9.6.1–9.6.5).

Mapped against the four archetypal futures in Section 7, the section sits primarily in the Discipline quadrant with Transformation pathways embedded in 9.4 and 9.5. Continue does not require any of these interventions, and the trajectory of roughly 2% annual ALAN growth (Kyba et al. 2017) extends without them. Discipline operationalizes the regulatory and infrastructural work in 9.1 through 9.3 and uses 9.6 to fill in the supporting architecture. Transformation requires 9.4 and 9.5 in addition. Collapse breaks the institutional preconditions all of these interventions depend on, and none of them function in a scenario where municipal governance, the SCC, and the rule-of-law architecture supporting environmental regulation are no longer operative. The section is honest about this. The interventions are designed for the futures where institutional capacity is preserved, and the case for that preservation sits outside the scope of what this report can argue.

Federal preemption removes Naval Station Norfolk and Norfolk Naval Shipyard from direct city regulation. The largest single concentration of high-mast lighting in the harbor is addressed through coordination rather than enforcement, and that limit is real. The Dillon Rule constrains several interventions to the state-enabling pathway, which is a multi-year legislative campaign in Richmond rather than a municipal decision. The *Central Hudson* commercial speech doctrine constrains the Phase 3 advertising prohibition in 9.2 and will require an evidentiary record that intermediate scrutiny actually accepts. *Penn Central* balances complicate any mandates on existing private fixtures, which is why the retrofit program in 9.3 is paired with phased compliance and the liability shield in 9.2. Regulatory capture is the standing risk in any governance body that includes industry representation, and the proportional-voting structure in 9.1 responds to it without eliminating it. None of these limitations argue against the interventions. They define the terrain the interventions have to operate within.

10 Discussion and Conclusion

Jamie Heffernan

This case study demonstrates that artificial light at night (ALAN) in Norfolk is not simply an environmental concern, but a complex socioecological system shaped by human behavior, infrastructure, and governance. Unlike hazards such as flooding or pollution that originate outside the system, ALAN is produced continuously by the same systems designed to support safety, economic activity, and daily life (Hölker et al., 2010a). This makes responsible lighting a fundamentally different challenge. The goal is not to eliminate light, but to manage it in a way that balances human needs with ecological and health outcomes.

10.1 Framing responsible lighting as a wicked problem

Framing responsible lighting as a wicked problem helps explain why meaningful progress remains limited and uneven. Wicked problems are defined by competing values, no single correct solution, and responsibility that is spread across multiple actors rather than centralized in one authority (Rittel & Webber, 1973). In Norfolk, the lighting system is controlled by a mix of stakeholders, including the City of Norfolk, Dominion Energy, VDOT, private developers, and federal installations, each operating under different priorities and constraints. Because no single entity governs the system as a whole, decisions are made independently, yet their impacts accumulate across the shared environment (Kolko, 2012). At the same time, social norms continue to shape these decisions. The widely accepted belief that brighter lighting improves safety reinforces patterns of over-illumination, even as research shows that excessive artificial light can create ecological disruption and human health impacts (Longcore & Rich, 2004). Together, these institutional and social dynamics create a system that is difficult to coordinate, slow to change, and resistant to straightforward solutions.

10.2 Study Limitations and future considerations

Another limitation is that a lot of this study is based on conceptual models and existing research rather than direct, large-scale data collection within Norfolk itself. While that still provides valuable insight into how the system behaves, it does not fully capture what is happening in every part of the city. The same goes for stakeholder perspectives. These were explored through analysis and role based thinking, but not through direct engagement with every group involved. Because of that, some voices, especially from communities that experience the most light exposure, may not be fully represented. These gaps show where future work needs to go. More local data collection and long-term monitoring would help track patterns and measure progress more clearly. At the same time, involving stakeholders more directly in the process would make sure decisions reflect the people most affected. Building on these areas would help turn this kind of system level understanding into real, practical change for Norfolk.

10.3 Conclusion

In conclusion, the future of responsible lighting in Norfolk will not be determined by technology alone, but by how decisions are made across the entire system. This case study shows that artificial light at night is not just a technical issue, it is something shaped by governance, infrastructure, social behavior, and the way different stakeholders interact with one another. The conceptual models and stakeholder analysis make it clear that light pollution continues not because solutions do not exist, but because the system is fragmented and difficult to coordinate. Decisions are spread across multiple actors, each working within their own limits, and those small decisions build into a much larger outcome over time. The analysis also shows that the system is already under stress. Ecological systems are being disrupted, human health is affected, and access to the night sky continues to decline. At the same time, these impacts are not evenly experienced. Some communities are exposed to higher levels of artificial light but have less ability to influence the decisions that shape their environment. Without changes in how the system is managed, these patterns will continue, leading to long-term impacts that are slow, cumulative, and difficult to reverse. The scenario analysis reinforces that Norfolk is not stuck in one path, but it also makes it clear that change will not happen on its own. Undesirable futures are the result of continuing current practices, while more desirable outcomes require intentional and coordinated action. This includes stronger governance, better data collection, increased public awareness, and a shift in how lighting is designed and used across the city. Treating light as something that needs to be managed, rather than something that is automatically beneficial, is a key step in that process. Moving forward, responsible lighting needs to be understood as a shared responsibility. It requires coordination between city agencies, utilities, developers, and the community, along with a willingness to challenge long-standing assumptions like the idea that brighter always means safer. By designing lighting systems more intentionally and considering both human and ecological needs, Norfolk has the opportunity to move toward a more balanced and resilient future. The path forward is not simple, but it is possible, and the choices made now will determine whether the system continues to degrade or begins to improve over time.

11 Moving Toward Responsible Lighting: Recommendations

Abby Lahey

Recognizing — The night is a shared commons whose value Norfolk has not yet treated with the deliberate care given to air quality or land use. Citizens for Responsible Lighting and DarkSky International have already translated scientific evidence into local advocacy. The voluntary Lights Out Hampton Roads program operates during migration windows, and Norfolk's 2026 legislative agenda includes support for low-light-impact lighting options.

Realizing — The LED retrofit window is closing now, and fixtures installed during this cycle will shape Norfolk's night for fifteen to twenty years. Millions of night-migrating birds cross the Atlantic Flyway through the city twice each year. Residents in historically redlined corridors east of downtown bear the highest current exposure burden. Without coordinated governance, regional radiance will continue to grow.

Acknowledging — The Dillon Rule constrains Norfolk to powers expressly granted by the Virginia General Assembly, so several recommendations require parallel state-level action. Naval Station Norfolk and Norfolk Naval Shipyard sit under federal jurisdiction beyond municipal enforcement. Dominion Energy is a regulated investor-owned utility whose financial structure opposes reductions in fixture count. Restrictions on illuminated advertising run into the constitutional protections courts have built around commercial speech, and mandates on existing private fixtures have to work within the limits courts have set on regulatory takings. Orbital lighting infrastructure sits beyond municipal authority entirely.

Emphasizing — The recommendations are sequenced by leverage and dependency rather than ease. Sustained advocacy from organized residents has to come first, because everything else depends on it. Without legal recognition,

municipal action lacks enforceable thresholds. The retrofit program turns recognition into measurable reductions, and migration-response codification can move in parallel. Strategic de-illumination comes last because it benefits most from the institutional infrastructure the prior recommendations build.

11.1 Sustain and Expand CRL Advocacy

CRL holds no formal regulatory power, which is why this recommendation comes first. The political pressure that creates the conditions for everything that follows has to come from organized residents. Without sustained coalition pressure across Hampton Roads, Norfolk negotiates with Dominion alone, and one city's request reads as a single utility problem rather than a regional political one.

We recommend that Citizens for Responsible Lighting:

- Expand the regional coalition across Hampton Roads to shift the political arithmetic in Richmond
- Lead public education in over-exposed neighborhoods first, with leadership development drawn from those neighborhoods
- Sustain pressure on the Virginia General Assembly for the state-level legislation the recommendations below require
- Build community pipelines for representation on any new lighting governance body, weighted toward residents whose exposure burden is highest

11.2 Recognize ALAN as a Pollutant

Light has none of the legal infrastructure that air, water, and noise pollution have. It currently sits in a nuisance regime where every harm is re-litigated case by case, and the burden of proof falls on residents who lack the resources to bring those cases. Recognition shifts that burden to emitters: once thresholds exist, exceeding them is the violation. Recognition also opens disparate-impact pathways for over-exposed communities and creates the legal authority that subsequent recommendations require.

We recommend that the Norfolk City Council:

- Amend the municipal code to recognize ALAN as a pollutant, with measurable thresholds for shielding, color temperature, brightness, and operating hours
- Require formal threshold-setting hearings in over-exposed neighborhoods, with input weighted toward residents whose exposure burden is highest
- Establish liability shield provisions for property owners in compliance with the standards

We further recommend that the Virginia General Assembly:

- Pass legislation giving Virginia municipalities the authority to regulate ALAN beyond what state law currently allows, and create a private right of action for light trespass that municipalities cannot establish on their own

11.3 Adaptive Spectrum and Shielding Retrofit, Funded by a Corporate Light-Pollution Levy

Norfolk's largest source of nighttime light is the lighting already installed, and the retrofit window is closing now. Fixtures specified during the current LED replacement cycle will shape the spectral character of Norfolk's night for fifteen to twenty years. Funding through a cap on emitters rather than a tax on emissions matters: a tax prices the externality and lets the activity continue, treating darkness as something wealthy emitters can buy out of, while a cap with penalties treats darkness as a commons whose limits are non-negotiable.

We recommend that the Norfolk City Council:

- Shield every unshielded outdoor fixture in the city within five years, starting with historically redlined corridors east of downtown
- Replace existing fixtures with color-tunable warm-spectrum LEDs as they reach end of life, capped at 2700K residential and 2200K in coastal and ecologically sensitive zones
- Establish a cap on the lumens major emitters (port floods, big-box parking lots, illuminated billboards) can put out, with violation fees flowing into a polluter-pays mitigation fund allocated by exposure burden
- Block emitters from passing compliance costs onto tenants through rent or onto customers through prices
- Place inspection authority with city staff, with violations filed in a public registry searchable by address

11.4 Codify Lights Out Hampton Roads with Bird Migration-Response Dimming

Norfolk sits on the Atlantic Flyway, and millions of night-migrating birds pass through twice each year. Disoriented birds are drawn toward illuminated buildings, where they collide with glass or exhaust their reserves circling. Voluntary participation has covered some buildings and missed others, and a migrating bird does not navigate around the buildings whose owners chose not to participate. Codification turns a coalition of willing participants into a continuous protective corridor.

We recommend that the Norfolk City Council:

- Codify Lights Out Hampton Roads into municipal ordinance, requiring non-essential exterior lighting on commercial and institutional buildings to be dimmed or extinguished during peak Atlantic Flyway migration windows
- Use seasonal calendars and weather-radar bird-density data to trigger real-time dimming
- Include exemptions for emergency, medical, navigation, and specifically authorized uses
- Collect bird-strike data during migration windows so future regulation can be grounded in Norfolk-specific evidence

11.5 Strategic De-Illumination

The cheapest, most effective, and most ecologically defensible response to over-lighting is to take it down. LED efficiency gains across global cities have produced more lighting at lower per-unit cost, brighter fixtures, longer hours, and expanded coverage. Refinement programs that swap fixture for fixture leave the underlying capacity in place.

Removal interrupts that dynamic. The program operates on statistical comparison against control sites rather than incident-driven thresholds, which would convert any single event into a program-killer regardless of causation.

We recommend that the Norfolk City Council and the Department of Public Works:

- Audit redundant and excessive outdoor lighting citywide, including high-mast, parking-lot, and building-mounted fixtures whose lumen output makes pole count alone an inadequate metric
- Set a phased removal target of twenty percent of streetlight poles in over-lit corridors by 2040
- Compare each conversion site against statistically matched control sites over multi-year windows for safety, traffic, and biodiversity outcomes. Build the program so a single incident cannot pause it without statistical evidence that the conversion caused the harm
- Give residents of the highest current exposure neighborhoods decision authority over which corridors near them are converted first
- Restore darkness or install native plantings as primary options at conversion sites, with replacement infrastructure secondary

11.6 Closing Declaration

We declare the need that:

- The Virginia General Assembly authorize Virginia municipalities to regulate ALAN beyond what state law currently allows, and create a private right of action for light trespass
- The State Corporation Commission allow Norfolk to reduce streetlight count and output without going through a multi-year tariff proceeding for every change
- A multi-municipal Hampton Roads coalition form to pursue these reforms together, since one city's request reads as a single utility problem and a regional coalition reads as a political one
- Federal facilities, including Naval Station Norfolk and Norfolk Naval Shipyard, coordinate with the city on lighting practices the recognition framework cannot reach through enforcement
- Orbital lighting infrastructure, including the proposed Reflect Orbital constellation, be addressed through federal authority that municipal governments cannot exercise

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Figures Not Included in Text

Item 2:



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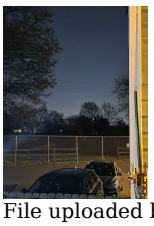
Item 8:



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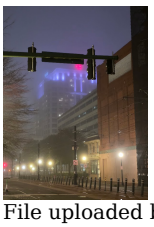

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Figure 9 (label: FIG-9): Not included in text.

Item 10:



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Figure 10 (label: FIG-10): Not included in text.

Item 11:

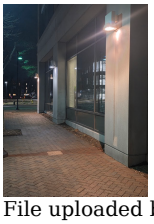

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Figure 11 (label: FIG-11): Not included in text.

Tables Not Included in Text

Item 3:

No file uploaded for Table 3.

Table 3 (label: TAB-3): Not included in text.

Item 4:



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Table 4 (label: TAB-4): Not included in text.

Item 5:



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Table 5 (label: TAB-5: System Components 1): Not included in text.

Item 6:



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Table 6 (label: TAB-6: System Components 2): Not included in text.

Item 8:



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Table 8 (label: TAB-8): Not included in text.
