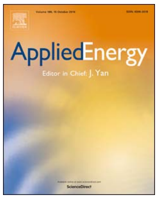
ARTICLE IN PRESS

Applied Energy xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Probabilistic assessment of aquatic species risk from thermoelectric power plant effluent: Incorporating biology into the energy-water nexus

Lauren H. Logan, Ashlynn S. Stillwell*

University of Illinois at Urbana-Champaign, Department of Civil and Environmental Engineering, 205 N. Mathews Ave., Urbana, IL 61801, United States

HIGHLIGHTS

- A risk assessment method quantifies aquatic species risk from power plant effluent.
- Aquatic species might be at risk even when power plants operate within permits.
- Risk-based analyses can support energy and water regulation and policy.

ARTICLE INFO

Keywords:
Aquatic ecology
Energy-water nexus
Policy
Thermal pollution
Thermoelectric power

ABSTRACT

As global populations grow, demand for generation of affordable and efficient electricity will likely increase, requiring tradeoffs between power generation and ecosystems sustainability, including water quality and species habitat. Once-through thermoelectric power plants, representing 30% of the electricity generation in the United States, withdraw and discharge large quantities of water for cooling purposes. This process can cause thermal pollution in waterways, adversely affecting aquatic communities. Incorporating biology into the energy-water nexus can aid decision-makers in identifying tradeoffs and more effectively assessing and managing aquatic ecosystems. To quantify thermal pollution and the risk posed to aquatic species, we created an adaptable, novel methodology that utilizes plume mixing and probability distribution analyses on temperature and flow data for both a power plant's discharge and the adjoining river. To assess risk, we developed a probability risk space that quantifies the probability of exceeding a given temperature. The Shawnee Fossil Plant on the Ohio River was selected to demonstrate the methodology, and three fish species with associated upper thermal avoidance limits were selected for comparison. Our results highlight that both the lateral and longitudinal location from the point of effluent mixing within the river affects the probability of thermal risk to aquatic species. A high degree of risk within a plume can reduce to a smaller total risk within the context of a large river cross-section. Our results emphasize the need for individualized risk assessment for Clean Water Act §316(a) requirements for power plant effluent temperature limits and National Pollutant Discharge Elimination System permits. These findings are applicable in policy-making, environmental mitigation, and power plant operations management.

1. Introduction

The energy-water nexus describes the interconnected nature of water and energy, with many studies centered on the power sector, urbanization, resource management, and/or policy development [1–11]. This linkage between energy and water will likely create challenges and opportunities as society aims to sustainably provide clean water and efficient power to a growing global population [12–17]. Researchers are aware of the vulnerability that power generation faces as water resources become increasingly strained [18–23]. Furthermore, the availability of water is both spatially and temporally dependent [24,25], with climate change expected to exacerbate the already uneven distribution of water on the planet via changes to precipitation patterns and air temperatures [26].

The reliability and generation potential of the thermoelectric power sector is directly linked to water availability [27–30]. Surface water resources in particular are becoming increasingly strained, such that water-scarce areas might experience an increased threat to human health and ecologic stability [31]. Even renewables, such as solar power, require water along the supply chain [32]. In 2010, water withdrawals for the thermoelectric power industry comprised 45% of total withdrawals in the United States [33]. Most of these withdrawals

---

* Corresponding author.
E-mail address: ashlynn@illinois.edu (A.S. Stillwell).
URL: http://stillwell.cee.illinois.edu (A.S. Stillwell).

http://dx.doi.org/10.1016/j.apenergy.2017.09.027
Received 30 November 2016; Received in revised form 29 August 2017; Accepted 9 September 2017

Please cite this article as: Logan, L.H., Applied Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.09.027

were from fresh, surface water sources, motivating an evaluation of the impacts of electric power generation on freshwater aquatic ecosystems.

Our work presents a probabilistic risk assessment to quantify the impacts of power plants on aquatic biology. We use empirical power plant temperature and withdrawal data from the Energy Information Administration (EIA), and river discharge data from the United States Geological Survey (USGS) to simulate thermal plume temperature and size conditions using CORMIX software. With curve fit and probability distribution analysis over 25 years of summer data analogous to a summer season, we numerically derive the probability of temperature exceedance within ambient, plume, and total river conditions. We demonstrate our unique method using the Shawnee Fossil Plant on the Ohio River, and highlight the results for three fish species with varying thermal preferences. Our novel method is applicable to power plant studies, for use in environmental policy and decision-making, and within the context of environmental mitigation of pollutants (e.g., thermal pollution).

2. Background

2.1. Thermoelectric power plant operations and cooling

Thermoelectric power plants produce waste heat loads that require large quantities of water and/or air to condense the working fluid [34–36], with water serving as the heat sink in approximately 99% of plants [37]. In once-through (or open-loop) wet cooled power plants, water is withdrawn from a source, circulated once to condense the working fluid, and returned to the source as discharge or effluent, often at elevated temperatures and/or degraded chemical state. Over 40% of U.S. electricity capacity is cooled with once-through cooling [37], representing approximately 30% of annual U.S. thermoelectric power generation [38,39]. Recirculating (or closed-loop) cooling systems withdraw less water from a source compared to once-through cooling, and recycle that water within the cooling system via a cooling tower or pond. More water is consumed per unit of generation (e.g., L/MW h) in recirculating cooling systems than in once-through cooling systems due to evaporative losses. Water withdrawal for electricity in the United States averages 95 L/kW h [37,40]. With hydroelectric power plants, hydropeaking to meet electricity demand is of concern in light of flow regime management and aquatic ecosystem degradation [41,42]. However, we focus on thermoelectric power plants only in this analysis. Of particular concern is the elevated temperature effluent from once-through power plants, representing a source of thermal pollution in surface water resources.

2.2. Temperature and biology

Aquatic species require certain conditions (thermal and otherwise) to thrive and reproduce effectively [43]. Much of the biology of species-temperature interactions are known, with many studies demonstrating the effects of thermal changes on aquatic species [44–52]. Majewksi and Miller [53] and Kennedy [54] note that a 1 °C change in water temperature can have devastating effects for sensitive aquatic species. Temperature is not only a direct regulator of life cycles, growth, and reproduction in organisms, but also inversely determines the dissolved oxygen content of water [54,55]. Furthermore, changes in water temperature can serve to reduce or alter suitable habitat within the water column, and thus pose an increase in risk to already changing aquatic ecosystems [56,57].

For most of the streams and rivers of the United States, a warming trend is expected due to climate change [58]. Shifts in ecosystem structure and functions can have unforeseen negative impacts that push localized ecosystems past thresholds or tipping points from which a return to pre-disturbance conditions might or might not be possible [59]. Furthermore, habitat changes as a result of climate change can have an impact on localized food webs [60]. All species innately have temperature preferenda, which include upper avoidance and lower avoidance limits [61], and a functional range within which an optimum exists [62].

An avoidance limit represents the temperature at which, on average, an organism will avoid or attempt to leave an area experiencing temperature extremes [56]. Literature values for temperature preferences and avoidance limits have been reported for a range of organisms, particularly fish species [63,64]. These limits should not be confused with lethal temperature, which causes acute mortality, nor should these limits be considered completely accurate in all scenarios. However, temperature limits generally provide good estimates for thermal studies such as our current work.

In our analysis, we use the term upper thermal avoidance limit (UTAL) to indicate the temperature at which a mobile species will attempt to leave the thermally affected area. We do not consider the effect of timing on the risk species face from thermal pollution (see Appendix A.2.3). For a more complete overview of temperature and its effects on species, refer to Majewski and Miller [53] or Langford [65].

2.3. Thermal pollution policy

The U.S. Clean Water Act (CWA) §316(a) governs effluent from thermoelectric power plants. Nationally, regulations require a blanket temperature limit of 32 °C to be maintained at thermoelectric power plant effluents, unless a thermal variance is granted by the National Pollutant Discharge Elimination System (NPDES). Any thermoelectric power plant operating as a utility is covered under the CWA 40 Code of Federal Regulations (CFR) Part 423 [66], and must comply with point-source pollution guidelines if its effluent enters any source waters of the United States [67]. Variance-seeking power plants must meet the criteria in 40 CFR §§125.72 and 125.73, and prove “the protection and propagation of a balanced indigenous community of shellfish, fish and wildlife in and on the body of water into which the discharge is to be made [40 CFR Ch. I (7/1/08 Edition)].” States may require stricter temperature limits, and/or provide limits in the form of discharged heat rates into receiving water bodies (e.g., a specified value of MBTU/h).

Cherry and Cairns [68] noted that although the qualitative biologic impacts of thermal pollution were understood, industry had then shown little interest in incorporating thermal preference information into power plant operations. Even today, policy-makers tend to view water, energy, and climate as three separate management issues [69], and stakeholder perspective plays a large role in nexus related policies [70]. Lefers et al. [71] and van Vliet et al. [28] note that climate change might increase surface water temperatures while decreasing water availability, increasing the likelihood of reductions in electricity production to meet CWA standards. To meet electricity demand, an increase in thermal variances might be necessary, which could further damage already vulnerable aquatic ecosystems.

2.4. Assessment of thermal pollution

Temperature preferenda and modeled or observed species response to temperature can support the aims of regulations under the CWA that protect species from point source thermal pollution. The quest for understanding thermal pollution from power plants to inform ecology and policy related decisions was fueled in the 1960s and 1970s (see [72–76]). Deterministic models that utilize energy fluxes within waterways have been developed to identify changes in temperature [43]. Other stochastic models use air temperature to predict water temperature, but are less effective when dealing with direct waterway impacts from sources like power plant effluent [43]. However, quantitatively identifying and relating direct risk from power plant effluent to species response remains as a gap in the literature.

Our work aims to fill this literature gap by creating a risk probability space that can be applied at various locations to many aquatic species. Developing a flexible methodology for multiple species can serve to aid