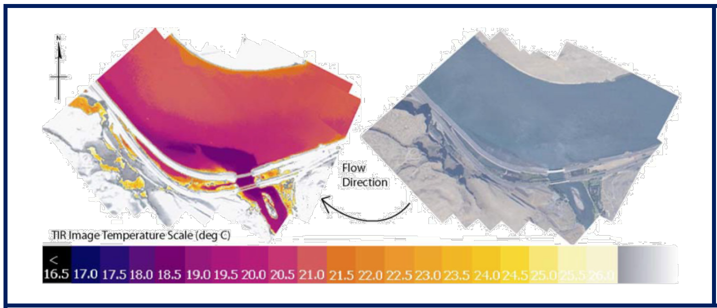

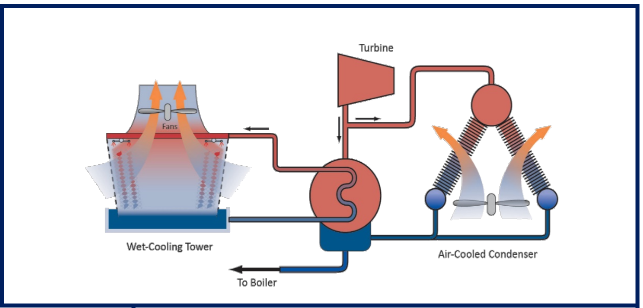

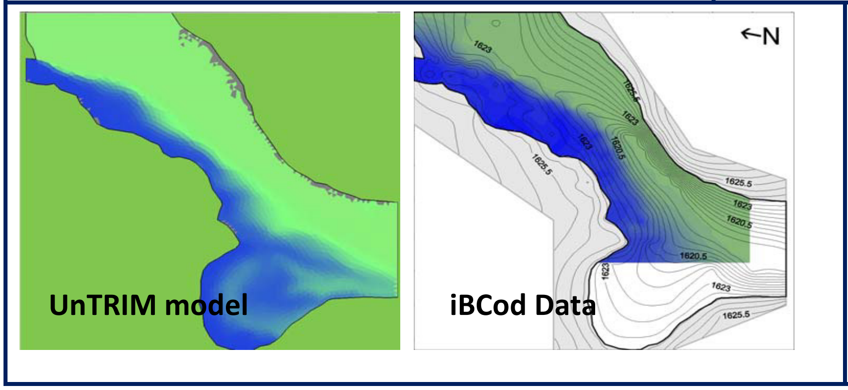

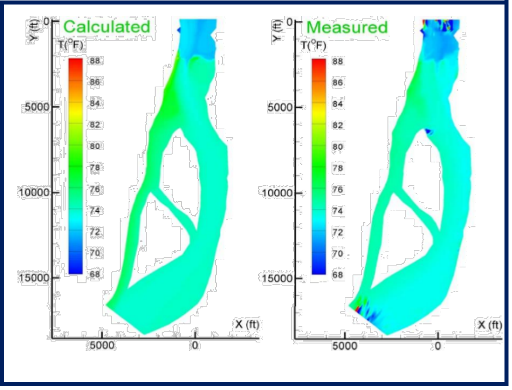

Thermal Discharges in NPDES Permits

Overview of Resources and Tools

EPA-833-F-23-007
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Office of Water

United States
Environmental Protection Agency

Thermal Discharges in National Pollutant Discharge Elimination System (NPDES) Permits: Overview of Resources and Tools

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1.0 Introduction

This document compiles existing resources, tools, references, and other information that National Pollutant Discharge Elimination System (NPDES) permitting authorities and other stakeholders may find useful for permitting and managing thermal discharges subject to Clean Water Act (CWA) requirements.[1]

1.1 Background

Temperature is a “master” environmental variable for aquatic ecosystems. It affects virtually all biota and biologically mediated processes, chemical reactions (notably the dissolution of oxygen), and structures the physical environment of the water column. Because they may alter ambient water quality, thermal discharges must be permitted. The permitting process helps ensure that thermal discharges do not cause unacceptable changes to the local aquatic community and habitat.

Many point source discharges convey sufficient heat load to affect ambient temperatures of receiving waters. Some facilities, such as power plants, use cooling water to eliminate waste heat from their industrial processes by discharging heated effluent. Others, such as wastewater treatment or industrial facilities, may have processes that discharge an effluent that is warmer than the receiving water. States typically have water quality standards (WQS) for temperature; if the volume of thermal effluent is significant and/or is elevated above an in-stream ambient or baseline temperature, the discharge may not meet the standards.

Interest in addressing thermal discharges has increased in recent years. In part, some studies have concluded that heated effluent can have a significant impact on fisheries, as spawning, habitat, and other environmental factors are affected.[2]

Additionally, increased focus on climate change is contributing to heightened awareness and concern regarding thermal discharges. As the temperatures of surface waters become warmer, and as weather, stream flow, and precipitation patterns become more unpredictable, thermal discharges from industrial facilities may have a more significant impact in receiving waters. Climate change is likely to modify the temperature of receiving waters for permitted discharges across much of the United States. Already, some EPA regions are documenting increased incidence of thermal discharge exceedances downstream of permitted discharge points. In a changing climate, there is a need to supplement existing CWA Section 316(a) documentation and to provide updated tools for both regulators and dischargers to inform the process by which 316(a) variances are evaluated.

In 1977, EPA released draft CWA section 316(a) guidance entitled “Interagency 316(a) Technical Guidance Manual and Guide For Thermal Effects Sections Of Nuclear Facilities Environmental Impact Statements”. This guidance provides valuable technical information on conducting 316(a) demonstrations, useful to both facilities and permitting authorities. This document supplements that guidance with more recent information on biological resources, technical resources, and case studies.

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[1] See disclaimer on page iii.

[2] See, for example, the 316(a) determination document for Brayton Point in Section 5.3.

1.2 Organization of the Document

Chapter 2.0 of this document provides an overview of NPDES permitting requirements applicable to thermal discharges, including development of technology-based effluent limitations and water quality-based limitations. The remainder of that chapter briefly describes the requirements applicable to a 316(a) thermal variance. This chapter also includes a brief discussion of CWA Section 316(b), which addresses cooling water intakes, and how a permit writer might consider both programs simultaneously.

Chapter 3.0 describes information on the thermal sensitivity of select biological resources in certain regions of the country. It summarizes available information on the thermal tolerances of Representative Important Species (RIS) in key regions of the U.S.: Pacific Northwest, Great Lakes, Middle Atlantic, and Inland Great Rivers. This chapter also summarizes the current knowledge about the heterogeneity of thermal regimes in waterbodies and the presence of thermal refugia: areas within a waterbody that provide pockets of different (usually cooler) temperatures for aquatic biota.

Chapter 4.0 provides information on models and tools for measuring temperature effects in waterbodies. These tools may be helpful in supporting a 316(a) variance request. It provides a summary of frequently used hydrodynamic models to study thermal plumes, mixing zones and other hydrological and water quality conditions; a summary of tools and approaches for monitoring temperature; and a review of technologies and operational strategies to mitigate thermal discharges.

Chapter 5.0 provides six case studies of well-designed 316(a) variance demonstrations for a variety of facilities and receiving waters. These documents illustrate the types of analyses and information needed in an assessment of thermal discharges. Based on these case studies, the chapter summarizes EPA's Recommended Best Practices for thermal study key design elements: current environmental characterization; overlapping regulatory zones and ecological habitats; long-term monitoring data; RIS selection; Thermal Monitoring; selection of thermal mixing models; thermal modeling scenarios; and bioassessments.

2.0 Thermal Discharges and NPDES Permitting

High temperature discharges can cause problems in receiving waters; many waterbodies have WQS for temperature. To protect these waters, NPDES permits often contain temperature limits for the effluent. This section describes how thermal discharges are addressed in permits.

2.1 NPDES Permitting Requirements Applicable to Thermal Discharges

CWA section 316(a) and its implementing regulations provide for variances from thermal effluent limitations in NPDES permits. EPA has only promulgated thermal limitations in effluent guidelines for two industrial sectors. Most thermal limitations in NPDES permits are driven by WQS. If a discharger is unable to comply with water quality-based effluent limitations at the point of discharge, applicable WQS may provide specifications for granting thermal mixing zones which allow portions of the waterbody to exceed the temperature criteria if the mixing zone provisions are met. If the permittee is unable to comply with the applicable thermal discharge limits at the edge of the regulatory mixing zone or at the point of discharge if a regulatory mixing zone is not appropriate, a permittee may seek relief from these standards by applying for a variance in accordance with CWA Section 316(a) and its implementing regulations.[3]

2.1.1 Technology-based Effluent Limitations

Technology-based effluent limitations (TBELs) in NPDES permits require a minimum level of treatment of pollutants for point source discharges based on available treatment technologies, while allowing the discharger to use any available control technique to meet the limits. For industrial (and other non-municipal) facilities, technology-based effluent limits are derived by:

- using national effluent limitations guidelines and standards (ELGs) established by EPA, and/or
- using best professional judgement (BPJ) on a case-by-case basis in the absence of applicable national guidelines and standards.

Certain EPA promulgated ELGs include TBELs for temperature, see for example, the Cement Manufacturing Effluent Guidelines and Standards (40 CFR Part 411) and Sugar Processing Point Source Category Subpart A - Beet Sugar Processing Subcategory (40 CFR Part 409). In the absence of applicable effluent guidelines for the discharge or pollutant, permit writers must identify any needed TBELs on a case-by-case basis. The site-specific TBELs reflect the BPJ of the permit writer, taking into account the same statutory factors EPA would use in promulgating a national ELG regulation, but they are applied to the circumstances relating to the applicant. For more information on TBELs, see NPDES Permit Writer's Manual (Chapter 5). For information on technologies for mitigating thermal discharges, see chapter 3.3 of this document.

2.1.2 Water Quality-based Effluent Limitations

When drafting an NPDES permit, a permit writer must consider the impact of the proposed discharge on the quality of the receiving water. Water quality goals for a waterbody are defined by the applicable state and/or tribal WQS for the receiving water. When analyzing the effect of a discharge on the

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[3] Regulations for submitting and reviewing thermal discharge variance requests are promulgated at 40 CFR Part 125, Subpart H.

receiving water, a permit writer could find that TBELs alone will not achieve the applicable WQS. In such cases, the CWA and its implementing regulations require development of water quality-based effluent limitations (WQBELs). WQBELs help meet the CWA objective of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters and the goal of water quality that provides for the protection and propagation of fish, shellfish, and wildlife, as well as recreation in and on the water (fishable/swimmable).

Most thermal effluent limitations for temperature contained in NPDES permits are based on applicable state and/or tribal WQS for the receiving water. Effluent limits for thermal discharges are generally expressed as a maximum and/or average temperature for the effluent but may also be expressed as the temperature increase at some location in the receiving water, or the change in temperature between the permittee's intake and outfall. The form in which the WQBEL for temperature is expressed is a function of how the applicable WQS is expressed.

2.1.3 Mixing Zones

If a discharger is unable to comply with WQBELs at the point of discharge, applicable WQS may provide specifications for granting thermal mixing zones which allow portions of the waterbody to exceed the temperature criteria as long as the mixing zone provisions are met.

As with other pollutants, mixing zones for thermal discharges may be authorized as allowed under applicable state or tribal regulations. Thus, permittees may request a thermal mixing zone. Permittees should work closely with permitting authorities to provide the data and information necessary for the permitting authority to determine an appropriate mixing zone, if any, on a site-specific basis for the discharge.

2.1.4 Section 316(a) Thermal Discharge Variance from Otherwise Applicable Thermal Limits

If the permittee is unable to comply with the applicable thermal limits at the edge of the regulatory mixing zone or at the point of discharge if a regulatory mixing zone is not appropriate, a permittee may seek relief from these standards by applying for a variance in accordance with CWA Section 316(a) and its implementing regulations. Less stringent alternative thermal effluent limitations (ATEL) may be included in a permit if the discharger properly demonstrates that thermal effluent limits necessary to meet the requirements of sections 301 or 306 are more stringent than necessary to assure the protection and propagation of a balanced, indigenous community (BIC) of shellfish, fish and wildlife in and on the body of water into which the discharge is made. This should take into account the cumulative impact of the thermal discharge together with all other significant impacts on the species affected.[4] Such demonstration may be provided through a combination of methods, including thermal modeling, ecological habitat surveys, field monitoring, and others.

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[4] Regulations at 40 CFR §125.71(c) define BIC: "The term balanced indigenous community (BIC) is synonymous with the term balanced indigenous population (BIP) in the Clean Water Act and means a biotic community typically characterized by diversity, the capacity to sustain itself through cyclic seasonal changes, presence of necessary food chain species and by a lack of domination by pollution tolerant species."

Expectations for Granting or Renewing a CWA Section 316(a) Thermal Variance

The following information describing how thermal variances are granted or renewed and incorporated into NPDES permits is from a memo dated October 28, 2008 titled "Implementation of Clean Water Act Section 316(a) Thermal Variances in NPDES Permits (Review of Existing Requirements)."

Regulations at 40 CFR part 125, Subpart H (§125.70-73) describe the information that the permittee must submit to support a request for a variance, as well as the criteria and process that the permitting authority will use to evaluate the request.

The burden of proof is on the permittee to demonstrate that it is eligible to receive an ATEL under section 316(a). This means the permittee must demonstrate to the permitting authority that a thermal effluent limit necessary to meet the requirements of sections 301 or 306 is more stringent than necessary to assure the protection and propagation of a BIC in and on the body of water into which the discharge is made (see 40 CFR § 125.73(a)).

In support of any proposed ATEL, the discharger must demonstrate that the ATEL will assure protection of the BIC, considering the "cumulative impact of its thermal discharge together with all other significant impacts on the species affected" (see 40 CFR § 125.73(a)).

When applying for an ATEL, an applicant must submit the supporting information and demonstrations identified and described in 40 CFR §§ 125.72 and 125.73. Among other things, the applicant must identify and describe (1) the requested ATEL, (2) the methodology used to support that limitation, (3) the organisms comprising the BIC along with supporting data and information, and (4) the types of data, studies, experiments and other information the applicant intends to use to demonstrate that the ATEL assures the protection and propagation of the BIC. 40 CFR § 125.72(a) and (b).

Existing dischargers may base their demonstration on the "absence of prior appreciable harm in lieu of predictive studies" (see 40 CFR §125.73(c)(1)). The demonstration of no appreciable harm must consider the "interaction of such thermal component with other pollutants and the additive effect of other thermal sources to a balanced, indigenous community…" (see 40 CFR § 125.73(c)(1)(i)). The regulations at 40 CFR §125.73(c)(2) further state that "in determining whether or not prior appreciable harm has occurred the Director shall consider the length of time in which the applicant has been discharging and the nature of the discharge."

With respect to renewal of a prior section 316(a) thermal variance, it is essential that permitting authorities require applicants to provide as much of the information described in 40 CFR § 125.72(a) and (b) as necessary to demonstrate that the alternative effluent limit assures the protection and propagation of the BIC. 40 CFR § 125.72(c). Such information may include a description of any changes in facility operations, the waterbody, or the BIC since the time the variance was originally granted.

Permit and Fact Sheet Requirements

NPDES permits containing a 316(a) thermal variance must include a fact sheet that complies with the general requirements of 40 CFR § 124.8. Among other things, the fact sheet must explain why the permitting authority believes any section 316(a) thermal variance included in the permit is justified, and it should contain a summary of any 316(a) thermal variance history from previous permits, if applicable (e.g., dates, determinations, limitations, etc.), as well as the basis for continuing the 316(a) thermal variance in the present permit.

Public Notice

40 CFR § 124.57 contains specific public notice requirements for permits requesting a 316(a) thermal variance. In addition to the public notice requirements at 40 CFR § 124.10(d)(1), the public notice for permits requesting a 316(a) thermal variance must contain the following elements:

1. A statement that the thermal component of the discharge is subject to effluent limitations under CWA sections 301 or 306 and a brief description, including a quantitative statement, of the thermal effluent limitations proposed under Section 301 or 306, and
2. A statement that a Section 316(a) request has been filed and that alternative less stringent effluent limitations may be imposed on the thermal component of the discharge under Section 316(a) and a brief description, including a quantitative statement, of the alternative effluent limitations, if any, included in the request.

Reassessment of Thermal Limits and Thermal Discharge Variance at Each Permit Renewal

Once a variance is granted, the discharger must still reapply for the variance each permit term. A permittee may request a renewal of its 316(a) thermal variance prior to the expiration of the permit. Any discharger holding a 316(a) thermal variance should be prepared to support the continuation of the variance with studies based on the discharger's actual operation experience (see note following 40 CFR 125.72).

Thermal effluent limitations and 316(a) variances granted to dischargers are not perpetual. A 316(a) thermal variance is an NPDES permit condition. It, therefore, expires along with the permit. The permitting authority must reassess the thermal limitations at each permit renewal, generally every 5 years. The permitting authority should assess any changes in effluent quality and any changes to the ambient waterbody. Because conditions in the receiving waterbody can change over time, 316(a) variance renewal requests should evaluate current receiving water conditions (river hydrology and water quality), changes in watershed land use, local BIC at the time of renewal, and the presence of any sensitive biological receptors such as species that have been newly listed as threatened and endangered since the original 316(a) demonstration."

Considering Cooling Water Intake Structures and Thermal Discharges Together

Management of thermal discharges may also need to consider CWA Section 316(b). EPA promulgated the 316(b) Existing Facility Rule in 2014 (79 FR 48300). There are several options for a facility to comply with the rule, including reducing the facility's cooling water intake flow to reduce its impact on biological resources. This assumes the amount of heat that a facility needs to discharge remains constant, and reducing the volume of cooling water would likely result in an increase in the temperature of the effluent. As such, permitting authorities may want to consider a balance of 316(a) and 316(b) regulatory aspects.

2.2 General Resources on Thermal Discharges

Below are several background documents that a reader might find useful; these include information on historical 316(a) guidance materials, current policy memos, and other relevant resources.

- EPA. 1974. Draft 316(a) Technical Guidance: Thermal Discharges. September 30, 1974. Available at https://nepis.epa.gov/Exe/ZyNET.exe/
- EPA. 1977. Draft Interagency 316(a) Technical Guidance Manual and Guide for Thermal Effects Sections of Nuclear Facilities Environmental Impact Statements. May 1, 1977. Available at https://www3.epa.gov/npdes/pubs/owm0001.pdf
- EPA, Region 1. 2002. Clean Water Act NPDES Permitting Determinations for Thermal Discharge and Cooling Water Intake from Brayton Point Station in Somerset, MA (NPDES Permit No. MA 0003654). Available at https://www.epa.gov/npdes-permits/brayton-point-station-power-plant-somerset-ma-final-npdes-permit
- EPA. 2008. Memorandum from James Hanlon (Office of Wastewater Management) to Water Division Directors, Regions 1-10. “Implementation of Clean Water Act Section 316(a) Thermal Variances in NPDES Permits (Review of Existing Requirements)” October 28, 2008. Available at https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-338.pdf
- EPA. 2013. EPA Oversight Addresses Thermal Variance and Cooling Water Permit Deficiencies But Needs to Address Compliance With Public Notice Requirements. Office of Inspector General. Report Number 13-P-0264. May 23, 2013. Available at https://www.epa.gov/sites/default/files/2015-09/documents/20130523-13-p-0264.pdf

Additionally, EPA maintains the NPDES Permit Writers’ Clearinghouse, a searchable database that houses hundreds of example documents covering a wide variety of topics. Documents include permits, templates, and training materials. Resources related to thermal discharges may be located by searching for “temperature” under the “Pollutants” menu or “316(a)” under the “Special Topics” menu, or perhaps using other search terms. Content is continually being added to the Clearinghouse and suggestions for materials to add are welcomed.

3.0 Effects of Thermal Discharges on Biological Resources of the Receiving Water

Assessing the impacts of thermal discharges on the biological community in the receiving water requires a detailed understanding of the biological resources present and the effect of thermal discharges on those resources.

This chapter summarizes available information on the thermal tolerances of Representative Important Species (RIS) in key regions of the U.S. such as the Pacific Northwest, Great Lakes, Middle Atlantic, and Inland Great Rivers. This chapter also summarizes the current knowledge about the heterogeneity of thermal regimes in waterbodies and the presence of thermal refugia: areas within a waterbody that provide pockets of different (usually cooler) temperatures for aquatic biota.

3.1 Temperature Tolerance of Select Key Aquatic Species in Certain Regions of the U.S.

3.1.1 Introduction

This section summarizes the thermal tolerance of select key aquatic species in four geographic areas: Pacific Northwest, Great Lakes, Middle Atlantic, and Inland Great Rivers. These regional summaries provide thermal tolerance data for permitting authorities to use in reviewing and considering thermal conditions in permits including site specific limitations, thermal mixing zone impacts, and CWA Section 316(a) demonstrations for alternative thermal limits.

The regional summaries in this section do not update or supplement any existing EPA guidance or policy document, nor should they be construed as providing direct instruction for selecting key species, RIS, or constituting a “pre-approved” RIS list for thermal studies in watershed drainages of the four regions. As with all thermal assessments, the selection of RIS requires extensive review of local species inventory and identifying habitats of interest and characterization of local conditions.

The information in this section will assist in validation of thermal tolerance information provided for specific species. In addition to thermal tolerance data for these regional species, EPA also provides additional references and websites to help guide the permitting authority to potential sources of thermal tolerance data for other locally important, thermally-sensitive, or rare species. The information and resources provided in this section should reduce the burden on the permitting authority and reduce the necessity of conducting *de novo* assessments of thermal tolerance as part of their review process.

The selection of a suite of key species for evaluation of potential thermal effects, commonly referred to in 316(a) and other thermal studies as the RIS, is very important. In this section, EPA identifies and justifies selection of generic RIS[5] which are often appropriate for inclusion in thermal studies along with their reported thermal sensitivity limits.

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[5] These are generic in the sense that they are widely applicable within a given geographic region. However, it is assumed that selection of RIS for any demonstration study will reflect the site-specific characteristics of the facility, environmental setting, and local biota.

3.1.2 Representative Important Species

General Concept

The concept of RIS is provided in CWA Section 316 regulations at 40 CFR Part 125.71. The definitions at 125.71(b) and (c) define RIS and the BIC they are intended to represent as:

> *"(b) Representative important species means species which are representative, in terms of their biological needs, of a balanced, indigenous community of shellfish, fish, and wildlife in the body of water into which the discharge of heat is made,"*
>
> *"(c) The term 'balanced, indigenous community' is synonymous with the term 'balanced, indigenous population' in the Act and means a biotic community typically characterized by diversity, the capacity to sustain itself through cyclic seasonal changes, presence of necessary food chain species and by a lack of domination by pollution tolerant species. Such a community may include historically non-native species introduced in connection with a program of wildlife management and species whose presence or abundance results from substantial, irreversible environmental modifications. Normally, however, such a community will not include species whose presence or abundance is attributable to the introduction of pollutants that will be eliminated by compliance by all sources with section 301(b)(2) of the Act; and may not include species whose presence or abundance is attributable to alternative effluent limitations imposed pursuant to section 316(a)."*

The RIS concept was further refined in the Draft Interagency 316(a) Technical Guidance Manual (EPA 1977) which indicated that, since it was not possible to study every species at a site, it would be necessary to identify and select one to fifteen RIS. The guidance for the selection of RIS that emerges from the draft guidance (EPA 1977) generally recommends the following criteria:

1. Species listed in state WQS as requiring protection.
2. Species listed as threatened and endangered.
3. Thermally sensitive species, which includes the most thermally sensitive species in the local area, including those species near the northern or southern boundaries of their natural ranges.
4. Commercially or recreationally valuable species.
5. Species that are critical to the structure and function of the ecological system, i.e., those that are necessary in the food chain or as habitat formers for the species included in the criteria above.
6. Species that are potentially capable of becoming nuisance species.
7. Species that are representative of the thermal requirements of important species but which themselves are not important.

Since publication of the 316(a) Technical Guidance Manual, some permitting authorities have developed their own RIS concept[6] and the scope of recommended species. For example, Maryland[7] provides a complete but simpler restatement of the federal RIS criteria that clarifies the importance of the spatial relationship between the facility and species presence or habitats in the local environment:

1. Species that are sensitive to adverse harm from operations of the facility (for example, heat-sensitive species);
2. Species that use the local area as spawning or nursery grounds, or both, including those species that migrate past the facility to spawn;
3. Species of commercial or recreational value, or both;
4. Species that are habitat formers and are critical to the functioning of the local ecosystem;
5. Species that are important links in the local food web;
6. Rare, threatened or endangered species; and
7. Potential nuisance organisms likely to be enhanced by plant operations.

These categories provide the state with a broad spectrum of ecological receptors and functions. Not all categories may be relevant for each site. These criteria help establish the initial dialogue between the permitting authority and permittee in the determination of appropriate site-specific RIS for both thermal mixing studies and 316(a) demonstrations.

RIS Selection Process

Selection of RIS begins with a comprehensive inventory of aquatic life to be found in the waterbody of interest and ends with the selection of appropriate important, local, or sensitive taxa for evaluation.[8] State-specific lists of fish and other wildlife relevant to each region are provided in each section. A baseline field monitoring program designed to gather data for the RIS species selection and evaluation process may be necessary, depending on the availability and quality of current biotic data for a specific watershed (Bogardus, 1981).

It is beyond the intent of this document to provide a full description of the RIS selection process. However, the basic elements of the RIS process—acquisition of local biotic data, determining appropriate species, and stepwise refinement and selection of RIS — is discussed in several documents, including those by Yoder (Yoder et al., 2006; Yoder, 2012) and Section 316(a) guidance issued by Indiana (IDEM, 2015).

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[6] Some states endorse the term “representative aquatic species” presumably to deemphasize the term “important” and in recognition that no one species is more important than another in terms of CWA protections (Yoder, 2012).

[7] See Maryland Title 26 Department of the Environment, Subtitle 08 Water Pollution; 26.08.03.04 Representative Important Species.

[8] See Appendix A to this section for species inventories for each state in the Pacific Northwest, Great Lakes, Middle Atlantic, and Inland Great Rivers regions. See Appendix B to this section for links to specific information on many species that are commonly found in these regions. Combined, this information will help to select an appropriate RIS.

For this document, EPA selected common, “generic” RIS species in general accordance with the guidance described above. These RIS provide basic coverage of aquatic species across several trophic levels, habitats, and ecological functions. To select this suite of RIS, EPA consulted several sources including: RIS selected in previous 316(a) studies from the region, scientific articles addressing habitat forming species (e.g., foundation species), compendia of locally important species (e.g., Michigan Sea Grant’s fish species list, the National Oceanic and Atmospheric Administration’s (NOAA’s) Great Lakes profile), general wildlife websites, and other sources.

Relevant sources of species-specific information, including trophic level, were obtained from FishBase (Froese and Pauly 2015), NatureServe Explorer, or other wildlife or watershed website sources. Website links for information on selected RIS species are provided in each section. In some cases, several candidate RIS were identified that fill similar or equivalent ecological roles or functions. In these cases, selection was further guided by the availability of reliable thermal sensitivity limit information for the species. Further information regarding selection of RIS for each region is provided in each section.

3.1.3 Thermal Sensitivity Limits

All aquatic species are susceptible to water temperatures that exceed both upper and lower thermal tolerances. Upper and lower lethal temperatures, including both acute and chronic tolerance limits, [9] vary widely between and among species and depend on many factors, including species type, genetics, developmental stage and thermal histories (Beitinger et al. 2000b). In compiling a thermal tolerance database for RIS species, EPA recorded both upper and lower thermal sensitivity limits, and the optimal habitat range (when available). Acute and chronic upper limits are likely to be most applicable for thermal studies. However, in cases where winter shutdowns (planned or otherwise) may occur, lower lethal temperatures may also be important (e.g., potential cold shock; see Donaldson et al. 2008).

Thermal Thresholds

For thermal demonstrations, most concern is focused on the impact of artificially elevated temperatures. Two types of upper lethal thermal sensitivity limits are typically used for potential impacts to species: the acute upper lethal temperature and the chronic or incipient upper lethal temperature.

Acute upper lethal temperature is the temperature at which death occurs when water temperature is raised rapidly beyond the tolerance of the organism (i.e., short duration stress resulting in rapid death). This value is sometimes termed the critical thermal maximum (CTM).

Chronic or upper incipient lethal thermal (UILT) limits involve continuous exposure to lethal temperatures for a long enough time to achieve significant mortality. Organisms can survive short-term exposure to thermal discomfort (e.g., above chronic lethal temperatures but below acute thresholds), but cannot survive sustained exposure to these temperatures. Many older studies report only CTMs, but

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[9] Note that the term “limit” has multiple meanings. In this context, it refers to the upper and lower bounds of an aquatic organism’s ability to tolerate changes in temperature. This is not to be confused with a discharge limit in an NPDES permit, which sets a maximum temperature for effluent. To help distinguish the two, the biological meaning has been adapted to “thermal sensitivity limit,” even though this term may not appear in the scientific literature as such.

Yoder (2012) suggests use of a site-specific conversion factor (if available) or a default conversion (e.g., UILT = CTM – 2°C) to arrive at an estimate of the UILT.

Analogously, there are also thermal minima, the lower lethal temperatures that limit natural distribution of species or may apply to scenarios in which warm-acclimated organisms are suddenly exposed to cold extremes (e.g., "cold shock" during power plant shut-downs). In the field, actual limits of temperature tolerance depend on the previous thermal history of the organism (e.g., Jobling 1981, Beitlinger et al. 2000b). For example, an organism that is acclimated to cold temperatures may have lower thermal tolerances than if it was acclimated to a warmer temperature. Organisms can also become seasonally adjusted to ambient water temperatures so that a higher temperature is required in the summer than in the winter to be lethal.

There are also a variety of alternative thermal endpoints that can be used or may be more appropriate to calculate site-specific, species-based thermal sensitivity limits. Some of these alternative endpoints reflect chronic exposure and responses include physiological optima (gametogenesis, growth, development, spawning), and behavioral endpoints (e.g., preferred range, upper avoidance). Yoder (2008) devised an integrated index, the Fish Temperature Model, incorporating a number of these endpoints including physiological or behavioral optimum, mean weekly average temperature for growth, an upper avoidance temperature, and an upper lethal temperature based on the UILT. The Fish Temperature Model has been applied to several waterbodies including the Ohio River (Yoder et al. 2006) and the Connecticut River (Yoder 2012) as a method of identifying potential RIS.

Sources of Thermal Thresholds

EPA collected thermal tolerance data from available scientific compilations of thermal sensitivity limits for several species (e.g., Coutant 1977; Wismer and Christie 1987; Beitlinger et al. 2000a; Yoder et al. 2006, Yoder 2012) or available life history and habitat information of candidate RIS (e.g., scientific literature, U.S. Fish and Wildlife Service (USFWS), and other documented sources). EPA used Google and Google Scholar to search for journals and additional sources that provide thermal tolerance data, specifically acute and chronic temperatures. For keywords, EPA used (1) the species name (either common or scientific) and (2) a variation of the phrase "thermal tolerance" (e.g., temperature tolerance, temperature range, maximum temperature, minimum temperature, critical thermal maximum, and lethal thermal maximum). These searches provided the temperature range for all species and the acute, chronic, and optimal temperatures for many species.

For some species, EPA found thermal sensitivity limits for different life stages (i.e., eggs, larvae, juvenile, and adults) that vary widely in their thermal sensitivity. When available, EPA included life history stage-specific data, since early life stages are often more sensitive to heat (and less able to avoid it) than juvenile or adult life stages. Where available, EPA also included optimal thermal range data, those temperatures that best promote population growth and stability. This information can be useful for comparison with thermal thresholds to indicate how much (or how little) increased temperature will result in a shift from preferred to potentially lethal conditions.

3.1.4 General Resources on Biological Impacts

Below are documents that that provide general information on the biological impacts of thermal discharges. Some of these are specific to certain regions of the United States, while others are more nationally applicable.

- Beitinger, T. L., W. A. Bennett, and R. W. McCauley. 2000a. Temperature tolerance of North American freshwater fishes exposed to dynamic changes in temperature. Environmental biology of fishes 58(3): 237-275.
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- BioAnalysts, Inc. 1999. Evaluation of seasonal cold-water temperature criteria. Prepared for the Idaho Department of Environmental Quality. Boise, ID.
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- Coutant, C. C. 1977. Compilation of temperature preference data. *Journal of the Fisheries Research Board of Canada* 34: 739-745.
- Dairyland Power Cooperative. 1982, 316(a) Demonstration Document Modification for the John P. Madgett Steam Electric Power Generating Station. October, 1982.
- Donaldson, M. R., S. J. Cooke, D. A. Patterson, and J. S. Macdonald. 2008. Review paper: Cold shock and fish. *Journal of Fish Biology* 73: 1491-1530.
- EA Engineering, Science and Technology (EA). 2008. Point Beach Nuclear Plant Evaluation of the Thermal Effects Due to a Planned Extended Power Uprate.
- EA Engineering, Science and Technology (EA). 2012. Final 316(a) Demonstration for the BP Whiting Refinery. Prepared for BP Refinery, IN. July 2012.
- EPA. 1977. Draft Interagency 316(a) Technical Guidance Manual and Guide for Thermal Effects Sections of Nuclear Facilities Environmental Impact Statements. Office of Water Enforcement, Permits Division, Industrial Permits Branch, Washington D.C.
- EPA. 2001. Summary of Technical Literature Examining the Physiological Effects of Temperature on Salmonids; Issue Paper 5. EPA 910-D-01-005. May 2001.
- EPA. 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. Region 10, Office of Water, Seattle, WA. EPA 910-B-03-002. April 2003.
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- HDR Engineering, Inc. 2009. Quad Cities Nuclear Station Adjusted Thermal Standard CWA 316(a) Demonstration: Final Draft. Prepared for Exelon Nuclear. November 2009.
- Indiana Department of Environmental Management (IDEM). 2015. “3.2 Type II Demonstrations (Representative Important Species)” in Guidance for Conducting a Demonstration as a Requirement for 316(a) Alternative Thermal Effluent Limitation Request.
- Jobling, M. 1981. Temperature tolerance and the final preferendum-rapid methods for the assessment of optimum growth temperatures. *Journal of Fish Biology* 19:439-455.

- McCullough, D. A. 1999. A review and synthesis of effects of alterations to the water temperature regime on freshwater life stages of salmonids, with special reference to Chinook salmon. Prepared for the EPA, EPA 910-R-99-010. Seattle, WA.
- We Energies (WE). 2012. Request for Alternative Effluent Limitation Under Wisconsin Statute §283.17. Wisconsin Electric Power Company Valley Power Plant. No WI-0000931-4.
- WESD. 1975. Clifty Creek Power Plant Thermal Discharge Study. Vol I. Technical Discussion. Prepared for Indiana-Kentucky Electric Corporation.
- Wismer, D. A. and A. E. Christie. 1987. Temperature relationships of Great Lakes fishes: A Data Compilation. Great Lakes Fishery Commission Special Publication No. 87-3.
- Yoder, C. O. 2008. Challenges with modernizing a temperature criteria derivation methodology: the fish temperature modeling system, pp. 1-1 to 1-19. *in* Robert Goldstein and Christine Lew (eds.). Proceedings of the Second Thermal Ecology and Regulation Workshop, Electric Power Research Institute, Palo Alto, CA.
- Yoder. C. O. 2012. Development of a Database for Upper Thermal Tolerances for New England Freshwater Fish Species. Midwest Biodiversity Institute Center for Applied Bioassessment & Biocriteria Technical Report MBI/2012-4-6.
- Yoder, C. O., E. T. Rankin, and B. J. Armitage. 2006. Re-evaluation of the technical justification for existing Ohio River mainstem temperature criteria. Report to Ohio River Valley Water Sanitation Commission. Technical Report MBI/05-02.

3.2 Pacific Northwest Rivers Representative Important Species Temperature Tolerance Data

Table 3-1 identifies 20 RIS for use in thermal studies in the Pacific Northwest Rivers region. EPA used the sources described above to identify candidate RIS for this region. From these candidate species, EPA selected species to include several trophic levels, species with commercial and/or recreational value, species with key ecological functions,[10] or special status/sensitivity. EPA then confirmed availability of good quality thermal sensitivity limit data for these species before finalizing the list.

Table 3-1 provides scientific and common names, trophic level and feeding mode for adults, and general characterization of species with regard to RIS criteria. EPA assigned trophic levels based on FishBase's diet composition descriptions (Froese and Pauly 2015) and/or descriptions of diet and primary food sources available on relevant state and federal wildlife websites. EPA assigned the following RIS criteria designations:

- Commercial and recreational value;
- Important food web link;
- Habitat formers;
- Locally abundant species;
- Nuisance species;

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[10] The role and feeding type of a RIS can vary widely during its life cycle. For assignment of trophic level and feeding model, the adult stage was used.

- Rare, threatened or endangered species;
- Thermal sensitive species.

These RIS designations and feeding modes may vary across life stages, but the final adult stage was used as the basis of the feeding classification.

The list of RIS for Pacific Northwest Rivers waters in Table 3-1 included 17 fish species, with an emphasis on salmonid and trout species: Chinook salmon (*Oncorhynchus tshawytscha*), Coho salmon (*Oncorhynchus kisutch*), Sockeye salmon (*Oncorhynchus nerka*), Steelhead/Rainbow trout (*Oncorhynchus mykiss*), Lahontan cutthroat trout[11] (*Oncorhynchus clarki henshawi),* Bull trout (*Salvelinus confluentus*), Brook trout (*Salvelinus fontinalis*), White sturgeon (*Acipenser transmontanus*), Green sturgeon (*Acipenser medirostris),* Mountain whitefish (*Prosopium williamsoni*), Mottled sculpin (*Cottus bairdii complex*)*,* Slimy sculpin (*Cottus cognatus),* Pacific Eulachon *(Thaleichthys pacificus),* Longnose sucker[12] (*Catostomus catostomus),* Chiselmouth (*Acrocheilus alutaceus*), longnose dace (*Rhinichthys cataractae)*, and Pacific lamprey (*Entosphenus tridentate).*

EPA added two native macroinvertebrates to this list — Western pearlshell (*Margaritifera falcata*) and American (or black) salmonfly (*Pteronarcys dorsata.*) — and one aquatic plant, northern water-milfoil (*Myriophyllum sibiricum)*. Together, these species meet the RIS criteria described in Section 3.1.

3.2.1 RIS Thermal Tolerances

As part of the selection process for the RIS for the Pacific Northwest Rivers region, EPA investigated sources of thermal tolerance data. Table 3-2 provides the data that were found. Few CWA Section 316(a) studies were available for review of prior RIS. EPA relied primarily on the thermal sensitivity limits compilations; particularly those focusing on salmonids, trout, and other cold water species (e.g., BioAnalysts 1999; EPA 2001; EPA 2003, McCullough 1999). For EPA's 2001 and 2003 compilations, EPA provided a modifier, either the table (T) or relevant text page (e.g., pXX), for easier reference. For less well-characterized RIS, data from academic articles on selected species were used. Thermal tolerance data were also available in reports from the USFWS, NOAA, and other sources.

3.2.2 Assumptions and Uncertainty

This section provides useful information to applicants and permit writers selecting RIS for thermal mixing zone and 316(a) demonstration studies in the Pacific Northwest Rivers. However, use of the data is subject to important assumptions and sources of uncertainty, including:

- Documented thermal limits came from many sources. Preference was given to the compilations done in support of temperature WQS (e.g., EPA 2001, EPA 2003).
- In selecting the thermal tolerances, preference was given to the most stringent (lowest) value; provided that the acclimation conditions in laboratory tests were standardized at 20°C +5°C.

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[11] Lahontan cutthroat trout were selected among the various known strains due to greater availability of thermal data. It has been assumed that this strain may tolerate warmer temperatures due to its native geographic distribution but EPA (2001) indicates this species is comparable to other salmon and trout in its response to warm water.

[12] Longnose sucker was substituted for mountain sucker due to the paucity of thermal data on the latter species.

- Since the thermal tolerance data represent the work of many researchers and laboratories, there are likely to be methodological differences between studies due to laboratory conditions, rearing practices, and condition/source of test organisms.
- Thermal limits were not available for all species' life stages and the identified value may or may not represent the most thermally sensitive life stage.
- In some cases, a surrogate species was used to estimate an RIS thermal limit.
- Selected RIS may not be representative of local species due to site-specific factors or because RIS life stages may only be present in certain habitat areas (e.g., spawning beds, nursery areas).
- Thermal limits represent one type of physical stress on the organism. In the field, species are likely to be subject to other natural (food availability, lack of refuge areas) and anthropogenic (pollution, entrainment) stressors that could affect thermal tolerance.

These sources of uncertainty should be considered on a site-specific basis. When considering relative uncertainty among regions, the assumptions and uncertainties applicable to RIS in the Pacific Northwest region are likely to be similar to those uncertainties and assumptions that must be made for other geographic regions.

Table 3-1. List of Selected RIS for Pacific Northwest Region

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
FISH				
Oncorhynchus tshawytscha	Chinook salmon	T-3 Piscivore	Commercial and recreational value; Thermal sensitive species	The range of chinook salmon is the Arctic and Pacific drainages from Point Hope, Alaska, to Ventura River, California. Chinook salmon is anadromous, migrating from streams to the ocean to grow and mature and returning to their natal streams to spawn. Populations may differ dramatically in the timing of adult migration and, to a lesser extent, timing of spawning. Fry may migrate to sea after as few as three months or as many as three years, but most stay one year instream. Instream, chinook feeds mainly on macroinvertebrates; after migrating from the stream, it feeds primarily on small forage fish. Adults eat mostly fishes. [1]
Oncorhynchus kisutch	Coho salmon	T-3 Piscivore	Commercial and recreational value; Thermal sensitive species	The range of coho production extends from Point Hope, Alaska to Monterey Bay, California. An anadromous species, spending 16-20 months at sea and returning to a variety of freshwater habitats including small, relatively low-gradient tributary streams for spawning and juvenile rearing, lakes, gravelly areas for spawning and over-wintering in off-channel alcoves and beaver ponds. They prefer complex instream structure (large and small woody debris) and shaded streams with tree-lined banks for rearing. [2,3]
Oncorhynchus nerka	Sockeye salmon	T-3 Piscivore	Commercial and recreational value; Thermal sensitive species	In North America, important spawning populations occur from the Columbia River northward. Sockeye is unique among the Pacific salmon in that juveniles rear for at least a year or two in lakes before migrating to saltwater. Many non-anadromous (kokanee) populations move from lakes into tributary streams to spawn, though some remain in lakes. Sockeye salmon rely on stream, lake and estuarine habitat as well as offshore waters during their lifecycle. They feed on small planktonic (drifting) organisms and a variety of terrestrial and aquatic insects. Eggs are laid in fine gravel and need cool water and good water flow (to supply oxygen) to survive. [4]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
Oncorhynchus mykiss	Steelhead / Rainbow trout	T-3 Piscivore	Commercial and recreational value; Thermal sensitive species	In the United States, steelhead trout are found along the entire Pacific Coast. Steelhead are anadromous. Unlike most salmon, steelhead can survive spawning, and can spawn in multiple years. Their diet consists of zooplankton while young; adults feed on aquatic and terrestrial insects, mollusks, crustaceans, fish eggs, minnows, and other small fishes (including other trout). Steelhead are capable of surviving in a wide range of temperature conditions. They do best where dissolved oxygen (DO) concentration is at least 7 parts per million. In streams, deep low-velocity pools are important wintering habitats. [3,5]
Oncorhynchus clarki	Cutthroat trout	T-3 omnivore	Commercial and recreational value; Locally abundant species	Found in many coastal Pacific coast drainages to Rocky Mountain interior areas. There are three distinct strains – sea-run, west slope and Lahontan cutthroat trout. Cutthroat trout usually inhabit and spawn in small to moderately large, clear, well-oxygenated, shallow rivers with gravel bottoms. Stream-resident cutthroat trout primarily feed on larval, pupal and adult forms of aquatic insects and adult forms of terrestrial insects. Coastal cutthroat trout feed on small fish such as sculpins, sand lance, salmon fry and herring. Adults consume a greater proportion of fish. [6]
Salvelinus confluentus	Bull trout	T-3 Piscivore, insectivore	Locally abundant species; Rare, threatened or endangered species; Thermal sensitive species	Bull trout are char native to the Pacific Northwest and western Canada. The historical range of bull trout includes major river basins in the Northwest. Bull trout require colder water temperature than most salmonids. Water temperature above 15 degrees Celsius (59 degrees Fahrenheit) is believed to limit bull trout distribution. Small bull trout eat terrestrial and aquatic insects but shift to preying on other fish as they grow larger. [7]
Salvelinus fontinalis	Brook trout	T-2 Omnivore	Nuisance species; Thermal sensitive species	Brook trout original range was northeastern North America, through the Great Lakes, and south along the Appalachian Mountains to Georgia. It is a non-indigenous invasive species in the Northwest; potentially outcompeting *S. confluentus*. Brook trout typically live in small, cold, clean streams, but can adapt to ponds and lakes or instream beaver ponds. Trout feed on aquatic and terrestrial insects, crustaceans and small fish. Brook trout can tolerate relatively acidic waters, but not temperatures much over 65° F. [8]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
Acipenser transmontanus	White sturgeon	T-2 Omnivore	Commercial and recreational value; Rare, threatened or endangered species	White sturgeon is the largest freshwater species in North America and inhabits large rivers throughout the Northwest. Significant populations occur in the Sacramento, Columbia, and Fraser Rivers. Some populations are anadromous, and others spend their entire lives in freshwater (landlocked). A bottom feeder whose young feed mostly on the larvae of aquatic insects, crustaceans, and mollusks while a significant portion of the diet of adult sturgeon consists of fish. [41]
Acipenser medirostris	Green sturgeon	T-2 Omnivore	Rare, threatened or endangered species; Important food web link	Green sturgeon is found along the west coast of Mexico, the United States, and Canada. They are the most broadly distributed, wide-ranging, and the most marine-oriented species of the sturgeon family. Adults live in oceanic waters, bays, and estuaries when not spawning. Limited feeding data indicates that adult eat benthic invertebrates including shrimp, mollusks, and amphipods. Adults typically migrate into fresh water beginning in late February, and spawning occurs from March-July, with peak activity from April-June. [9, 11]
Prosopium williamsoni	Mountain whitefish	T-2 Omnivore	Locally abundant species; Important food web link; Thermal sensitive species	Mountain whitefish is one of the most widely distributed salmonid fish of western North America. It generally inhabit clear, cool waters (< 20° C) of high elevation streams, rivers, and lakes. Spawning occurs during late fall to early winter (Oct - Dec) in shallow areas of small tributaries or shoreline areas of lakes, primarily over gravel, rubble, or cobble bottoms. Mountain whitefish are demersal feeders, consuming a range of benthic invertebrates, including insect larva, gastropods, and small crustaceans. [10, 11]
Cottus bairdii complex	Mottled sculpin	T-2 omnivore	Locally abundant species; Important food web link	Mottled sculpin has a broad distribution, with disjunct eastern and western populations including the Columbia River drainage from British Columbia south to Oregon and east to Wyoming. They are generally found in gravel or rocky rubble substrates in swift waters of headwaters, creeks, and small rivers and occasionally in lakes or reservoirs. They are benthic ambush predators, consuming primarily aquatic insect larvae (e.g., flies and midges), crustaceans, small fishes, and fish eggs. [12]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
Cottus cognatus	Slimy sculpin	T2- Omnivore	Locally abundant species; Important food web link	Continental range includes Atlantic, Arctic, and Pacific basins of Alaska and most of Canada, south to Washington, Idaho, Montana, Iowa, and St. Lawrence-Great Lakes basin. Typical habitats are deep oligotrophic lakes and swift rocky-bottomed streams (spring-fed streams in south). Sometimes this sculpin occurs in brackish water. Eats mainly immature aquatic insects and crustaceans obtained from bottom; also eats other invertebrates, fish eggs, and plant material. [3, 13, 14]
Thaleichthys pacificus	Pacific Eulachon	T-2 Omnivore	Rare, threatened or endangered species; Important food web link; Thermal sensitive species	Eulachon range from northern California to southwest Alaska and into the southeastern Bering Sea. They are a valuable food source for many animals because of extremely high oil content. Smelt typically spend three to five years in saltwater before returning to freshwater to spawn in late winter through mid-spring. Climate change is also expected to change the timing and volume of spring flows in Northwest rivers and these changes could have a negative effect on spawning success. [15]
Catostomus catostomus	Longnose sucker	T2-Omnivore	Locally abundant species; Important food web link	The longnose sucker is the most widespread sucker in the North and is found in large numbers in most clear, cold waters throughout Canada and Alaska, and south to western Maryland, north to Minnesota, west and north through northern Colorado, and through Washington. Longnose sucker fry feed on zooplankton and diatoms, making a transition to benthic invertebrates. Adults are generally omnivorous, consuming amphipods, cladocerans, benthic insects (mainly Chironomidae), and other invertebrates, depending on food availability. [16]
Acrocheilus alutaceus	Chiselmouth	T-2 Omnivore; (grazer)	Important food web link	Range includes the Columbia and Fraser River systems in British Columbia, Washington, Oregon, Idaho, Nevada, and parts of central Oregon. It occurs in flowing pools and runs over sand and gravel in creeks and small to medium rivers. It also occurs abundantly along the margins of lakes. Adults feed mainly on diatoms, also on filamentous algae; young feed on surface insects. In British Columbia, spawning occurs usually in late June-early July when water temperatures reach about 62.5°. [3,17]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
Rhinichthys cataractae	Longnose dace	T-2 Omnivore	Locally abundant species; Important food web link	Generally distributed above 40 degrees North from coast to coast. Inhabit rubble and gravel riffles (sometimes runs and pools) of fast creeks and small to medium rivers; also in rocky shores of lakes. Feed on mayflies, blackflies, and midges. [18]
Entosphenus tridentatus	Pacific Lamprey	T-2; Parasitic	Locally abundant species; Thermal sensitive species	Pacific lampreys are widely distributed around the Pacific Rim including Alaska, Canada, Washington, Oregon, Idaho, and California to Baja California. Their distribution includes major river systems such as the Fraser, Columbia, Klamath-Trinity, Eel, and Sacramento-San Joaquin Rivers. Pacific lampreys are anadromous, adults are parasitic and feed on a variety of fish, including pacific salmon, flatfish and rockfish and are preyed upon by sharks and other marine animals. Pacific lampreys spawn in similar habitats to salmon; in gravel bottomed streams, at the upstream end of riffle habitat. [19]
INVERTEBRATE				
Margaritifera falcata	Western Pearlshell	Filter feeder	Habitat formers; Important food web link	*M. falcata is* found in Pacific drainages from California to British Columbia and southern Alaska. *M. falcata* prefer cold clean creeks and rivers that support salmonid populations. They can inhabit headwater streams less than a few feet wide but are more common in larger rivers. Host fish for *M. falcata* are thought to include native and non-native trout and salmon, including cutthroat trout, rainbow trout, Chinook salmon, coho salmon, redband trout, sockeye salmon, steelhead trout, brook trout, and brown trout. Invasive species that compete with native fish may affect *M. falcata*. [20]
Pteronarcys dorsata.	American Salmonfly	Detritivore (shredder)	Important food web link	Range includes the Coast, Cascade, Rocky, and Sierra Nevada Mountains northward to Alaska and Yukon and southward to Mexico. They require well-oxygenated water, so they thrive in swift, bouldery, and riffly stretches of the river. They feed on large organic materials (i.e., shredders) and are an important food source for salmonids. [21,22]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
PLANT				
Myriophyllum sibiricum	Northern water-milfoil	Primary producer	Nuisance species; Habitat formers; Important food web link	Northern milfoil is widely-distributed around the northern half of North America, Europe, and western Asia. It is a native plant which commonly grows in lakes, rivers, and ponds throughout Pacific northwest. It provides cover for fish and invertebrates. Supports insects and other small animals and waterfowl occasionally eat the fruit and foliage. [23]

[1] Numbers in brackets denote references found in Table 3-3.

Table 3-2. Thermal Tolerances of RIS for the Pacific Northwest Region

		Acute				Chronic (°C)				Optimal Thermal Range			
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
FISH													
Oncorhynchus tshawytscha	Chinook salmon	Eggs				Eggs				Spawning	12.8	5.6	24
		Larvae				Larvae				Incubation	9-10	5	25(p31)
		Juvenile				Juvenile	24.9		25(T4)	Growth	15.6	10.0	25(p40)
		Adult				Adult				Migration	15		47
Oncorhynchus kisutch	Coho salmon	Eggs				Eggs				Spawning	14	4	26(T1)
		Larvae				Larvae				Incubation	12	1.3	25(p33)
		Juvenile				Juvenile	25.0		25(T4)	Growth	16	10	26(T1)
		Adult				Adult				Migration	17-18		26(T1)
Oncorhynchus nerka	Sockeye salmon	Eggs				Eggs				Spawning	14	4	26(T1)
		Larvae				Larvae				Incubation	10	8	25(p35)
		Juvenile				Juvenile	23.5		25(T4)	Growth	16.7	11.7	25(p40)

		Acute				Chronic (°C)				Optimal Thermal Range			
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
		Adult				Adult				Migration	19.5	13.4	48
Oncorhynchus mykiss	Steelhead / Rainbow Trout	Eggs				Eggs				Spawning	14	4	26(T1)
		Larvae				Larvae				Incubation	12/10	11/7	25(p36)
		Juvenile				Juvenile	25-26		25(T4)	Growth	17	15	49
		Adult				Adult				Migration	17	16	50
Oncorhynchus clarki	Cutthroat Trout (Lahontan)	Eggs				Eggs				Spawning			
		Larvae				Larvae				Incubation	10	7	25(p37)
		Juvenile				Juvenile				Growth	22	13	25(p92)
		Adult				Adult	26-25		25 (p94)	Migration			
Salvelinus confluentus	Bull Trout	Eggs				Eggs				Spawning	9	6	25,51
		Larvae				Larvae				Incubation	6	2	25(p18)
		Juvenile	28.9		31	Juvenile	23-20.9		25, 31	Growth	12	8	26(T2)
		Adult				Adult				Migration	16		26(p26-27)
Salvelinus fontinalis	Brook Trout	Eggs				Eggs				Eggs			
		Larvae				Larvae	20.1		28	Larvae			
		Juvenile				Juvenile	24-25.8		28	Juvenile			
		Adult	28.7-29.8		28	Adult				Adult	11.7	6.1	8
Acipenser transmontanus	White Sturgeon	Eggs				Eggs				Spawning	18	10	52
		Larvae	20-21		27	Larvae	20	8	45	Incubation	20	6	53

		Acute				Chronic (°C)				Optimal Thermal Range			
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
		Juvenile				Juvenile				Growth	20	15	27, 54
		Adult				Adult				Migration	5.5	12.1	55
Acipenser medirostris	Green Sturgeon	Eggs				Eggs	17-18		33	Eggs	16	14	56
		Larvae				Larvae	22		33	Larvae	20	18	56
		Juvenile				Juvenile				Juvenile	19	15	34, 56
		Adult				Adult				Adult			
Prosopium williamsoni	Mountain whitefish	Eggs				Eggs	15-12		39	Spawning	5.5-4.4	3-0	39
		Larvae				Larvae				Incubation	<6.0		39
		Juvenile	21.6		46	Juvenile	16.8		46	Juvenile	12	9	27
		Adult				Adult	23.2-23.9		27, 39	Adult	12	9	27
Cottus bairdii complex	Mottled Sculpin	Eggs				Eggs				Eggs	16.1	5.0	28
		Larvae				Larvae				Larvae	17.3	7.8	28
		Adult	30.9		28, 35	Adult	24.3		35	Adult	16.2		35
Cottus cognatus	Slimy Sculpin	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	26.1-25	2.5	28, 35	Adult	22.8		35	Adult	13	11	28, 35
Thaleichthys pacificus	Pacific Eulachon	Eggs				Eggs				Spawning	10	0	36
		Larvae				Larvae				Incubation			

		Acute				Chronic (°C)				Optimal Thermal Range			
Species	Common Name	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]
		Juvenile				Juvenile				Growth			
		Adult	26-29		37	Adult				Migration			
Catostomus catostomus	Longnose Sucker	Eggs				Eggs				Eggs	15.2	10	29, 35
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult				Adult	27-26.5		28	Adult	17	8	28
Acrocheilus alutaceus	Chiselmouth	Eggs				Eggs				Eggs	18	13	56
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult				Adult				Adult			
Rhinichthys cataractae	Longnose Dace	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	31.4		28,29	Adult				Adult	14.7	7.2	28
Entosphenus tridentatus	Pacific Lamprey[2]	Eggs				Eggs	22.2		19	Eggs			
		Larvae	29.5		29	Larvae				Larvae	18	10	58
		Adult				Adult				Adult			
INVERTEBRATE													
Margaritifera falcata	Western Pearlshell[3]	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae	10-15		20

		Acute				Chronic (°C)				Optimal Thermal Range			
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
		Juvenile	33.2		44	Juvenile				Juvenile			
		Adult	36.1		44	Adult				Adult			
Pteronarcys dorsata	American Salmonfly	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Nymph	29.5		29	Nymph				Nymph	<20	>10	59
		Adult				Adult				Adult	<20	>10	59
PLANT													
Myriophyllum sibiricum	Northern water-milfoil[4]	NA				NA				Seedling		≤0	40

[1] Numbers denote references found in Table 3-3.

[2] Values taken from congeners include: *Lampreta planeri* (19) and *Lampreta appendix* (29).

[3] Optimal temperature tolerances are based on the following species: *Epioblasma brevidens*, *Epioblasma capsaeformis*, and *Lampsilis fasciola.*

[4] *M. sibiricum* requires winter water temperatures to be ≤0ºC to germinate turions (winter cold treatment).

Table 3-3. List of References for RIS (Table 3-1) and Thermal Tolerances (Table 3-2)

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3.3 Great Lakes Representative Important Species Temperature Tolerance Data

Table 3-4 identifies 19 RIS for use in thermal studies in the Great Lakes region.[13] EPA used several regional sources including the 316(a) demonstrations for several facilities (i.e., BP Whiting Refinery (EA 2012); Point Beach Nuclear Plant (EA 2008); and Valley Power (WE 2012)) and several Great Lakes states' watershed inventories to identify candidate RIS for this region. From these candidate species, EPA selected species to include several trophic levels, species with commercial and/or recreational value, species with key ecological functions,[14] or special status/sensitivity. EPA then confirmed availability of good quality thermal sensitivity limit data for these species before finalizing the list.

The list of RIS for coastal and riverine Great Lakes waters in Table 3-4 included several fish species: northern pike (*Esox lucius*), lake trout (*Salvelinus namaycush*), white bass (*Morone chrysops*), smallmouth bass (*Micropterus dolomieu*), walleye (*Sander vitreus*), yellow perch (*Perca flavescens*), burbot (*Lota lota*), lake whitefish (*Coregonus clupeaformis*), lake sturgeon (*Acipenser fulvescens*), bloater (*Coregonus hoyi*), alewife (*Alosa pseudoharengus*), brown bullhead (*Ameiurus nebulosus*), black crappie (*Pomoxis nigromaculatus*), mottled sculpin (*Cottus bairdii*), spottail shiner (*Notropis hudsonius*), and American gizzard shad (*Dorosoma cepedianum*). To this list of fish, EPA added a native freshwater mussel (*Strophitus undulates*), zebra mussel (*Dreissena polymorpha*), burrowing mayfly (*Hexagenia spp.*), and scud (*Gammarus fasciatus*) to represent invertebrates, *Microcystis aeruginosa* to represent aquatic plants and algae, and opossum shrimp (*Mysis relicta*) and amphipods (*Diporeia spp*.). Together, these species represent the full array of RIS criteria described in Section 3.1.

3.3.1 RIS Thermal Tolerances

As part of the selection process for the RIS for the Great Lakes region, EPA investigated sources of thermal tolerance data. Table 3-5 provides the data that were found. The Point Beach 316(a) study (EA 2008) and the thermal data compilations of Wismer and Christie (1987), Beitinger et al. (2000a), and Yoder (Yoder et al. 2006; Yoder 2012) provided temperature tolerances for many of the selected species. Additionally, EPA searched several government agency websites for habitat requirement and thermal tolerance reports. Thermal tolerance data were also available in reports from the EPA, the U.S. Department of Commerce, and other sources.

3.3.2 Assumptions and Uncertainty

This section provides useful information to applicants and permit writers selecting RIS for thermal mixing zone and 316(a) demonstration studies in the Great Lakes. However, use of the data is subject to important assumptions and sources of uncertainty, including:

- Documented thermal limits come from myriad sources (some quite dated). While all sources of thermal limit data were treated equally, there are likely to be methodological differences between studies due to laboratory conditions, rearing practices, and condition/source of test organisms.

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[13] For the purposes of this document, the Great Lakes region includes the coastal Great Lakes adjacent to the states of Illinois, Indiana, Michigan, Minnesota, Ohio, Pennsylvania, and New York.

[14] The role and feeding type of an RIS can vary widely during its life cycle. For assignment of trophic level and feeding model, the adult stage was used.

- Thermal limits were not available for all species' life stages and the identified value may or may not represent the most thermally sensitive life stage.
- In some cases, a surrogate species was used to estimate an RIS thermal limit.
- Selected RIS may not be representative of local species due to site-specific factors or because RIS life stages may only be present in certain habitat areas (e.g., spawning beds, nursery areas).
- Thermal limits represent one type of physical stress on the organism. In the field, species are likely to be subject to other natural (food availability, lack of refuge areas) and anthropogenic (pollution, entrainment) stressors that could affect thermal tolerance.

These sources of uncertainty should be considered on a site-specific basis. When considering relative uncertainty among regions, the assumptions and uncertainties applicable to RIS in the Great Lakes region are likely to be similar to those uncertainties and assumptions that must be made for other geographic regions.

Table 3-4. List of Selected RIS for Great Lakes Region

Species	Common Name	Trophic Status	RIS Status	RIS Justification
FISH				
Esox lucius	Northern Pike	T-3 piscivore	Commercial and recreational value; Important food web link	Voracious predators that can have significant impacts on their prey species; popular game fish (https://www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614_82648---,00.html)
Salvelinus namaycush	Lake Trout	T-3 piscivore	Thermal sensitive species; Commercial and recreational value	This fish strongly prefers frigid water temperatures; Lake trout are avidly sought after by both commercial and sport anglers, for food as well as for the sport (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82519---,00.html)
Morone chrysops	White Bass	T-3 piscivore	Commercial and recreational value; Locally abundant species	The white bass occurs in Lake Ontario, Lake Erie, Land Huron and Lake St. Clair. It is an important game fish, particularly in Lake Erie (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82599---,00.html)
Micropterus dolomieu	Smallmouth bass	T-3 piscivore	Commercial and recreational value	Smallmouth bass are one of the top game and food fish (https://www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614_82601---,00.html)
Sander vitreus	Walleye	T-3 piscivore	Locally abundant species; Commercial and recreational value	Present in all five Great Lakes; target of recreational and commercial fisheries for hundreds of years (https://www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614_82666---,00.html)
Perca flavescens	Yellow Perch	T-3 piscivore	Commercial and recreational value; Locally abundant species	Yellow perch are the most frequently caught game fish in Michigan. They inhabit all the Great Lakes, with greatest Michigan concentrations in Lake Erie, Lake St. Clair, Saginaw Bay, the eastern end of the U.P. and southern Michigan (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82677---,00.html).
Lota lota	Burbot	T-3 piscivore	Locally abundant species; Commercial and recreational value	The burbot is a large, abundant, and delicious fish; important for ice fishing recreation; Burbot inhabit a wide range of depths, moving shallow to spawn in winter and using deeper areas in summer (https://www.dnr.state.mn.us/minnaqua/speciesprofile/burbot.html)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Coregonus clupeaformis	Lake Whitefish	T-2 omnivore	Commercial and recreational value; Important food web link	Has long been a mainstay of the commercial catch in the Great Lakes because of its exceptional flavor, convenient size, and habit of schooling; whitefish eggs are consumed by yellow perch, ciscoes, burbot, and even other whitefish. Young whitefish fall prey to lake trout, northern pike, burbot, walleye, and other fish-eating predators (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82676---,00.html)
Acipenser fulvescens	Lake Sturgeon	T-2 omnivore	Rare, threatened or endangered species	A barometer of the health and diversity of the entire Great Lakes ecosystem (https://www.fws.gov/midwest/sturgeon/sturgeonBrochure.htm); Lake sturgeon are listed as either threatened or endangered by 19 of the 20 states within its original range in the United States (https://www.fws.gov/southeast/wildlife/fishes/lake-sturgeon/)
Coregonus hoyi	Bloater	T-2 omnivore	Commercial and recreational value; Thermal sensitive species	Important forage fish, especially as juveniles, which are utilized by salmon and nearshore lake trout (http://www.glfc.org/pubs/lake_committees/common_docs/5B_Bunnell_lake_michigan_BT_2008_Final.pdf). Bloaters also support a commercial fishery in Lake Michigan; prefer low water temperatures (EA, 2008); formerly occurred in all of the Great Lakes except Lake Erie; now evidently extirpated in lakes Ontario and declining in Lakes Superior and Huron (http://www.iucnredlist.org/details/5366/0)
Alosa pseudoharengus	Alewife	T-2 omnivore	Commercial and recreational value; Nuisance species; Important food web link	Non-native; The introduction of the alewife can restructure a lake's food web leading to decline of native planktivorous salmonids (e.g., whitefish). In the Great Lakes, extermination of the lake herring and decline of chub species in the Great Lakes has been partially attributed to the alewife (http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=490)
Ameiurus nebulosus	Brown Bullhead	T-2 omnivore	Commercial and recreational value	Considerable market and recreational value; they thrive in warm water, and can tolerate higher pollution and carbon dioxide levels, and lower oxygen levels than most other fish species (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82672---,00.html)
Pomoxis nigromaculatus	Black Crappie	T-2 omnivore	Commercial and recreational value	Black crappie are a popular sport and food fish (https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82673---,00.html))

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Cottus bairdi	Mottled Sculpin	T-2 omnivore	Locally abundant species	Present in all five Great Lakes (https://www.glerl.noaa.gov/pubs/fulltext/2018/20180006.pdf))
Notropis hudsonius	Spottail Shiner	T-2 omnivore	Commercial and recreational value	Important bait source for fishery (https://spo.nmfs.noaa.gov/sites/default/files/legacy-pdfs/leaflet608.pdf)
Dorosoma cepedianum	American Gizzard Shad	T-1 planktivore	Locally abundant species; Commercial and recreational value	Present in all five Great Lakes, important bait fish for fishery (http://www.glerl.noaa.gov/seagrant/GLWL/Fish/herrings/herrings.html); important bait fish for fishery (https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=492)
INVERTEBRATE				
Strophitus undulatus	Freshwater Mussel	filter feeder	Habitat formers; Important food web link; Thermal sensitive species	Freshwater mussels are found across the U.S. In good habitat, mussels will form dense concentrations called mussel beds, which can contain thousands of individuals sometimes representing dozens of species. Mussels are food for fish, raccoons, river otters, mink and muskrats, and mussel beds create habitat for many other invertebrates. Because mussels release unwanted food items in a mucus strand, they transfer suspended food from the water column to the stream bed, making this food available for aquatic insects and other small animals. As filter feeders, they clean harmful bacteria and parasites from the water. (http://molluskconservation.org/MUSSELS/Habitat.html)
Dreissena polymorpha	Zebra Mussel	filter feeder	Nuisance species	Non-native; Zebra mussels are considered one of the most damaging invasive species introduced to this country; cause economic damage by clogging boat cooling systems and the intake pipes of water treatment and power plants; have deleterious effects of local ecosystems; reduce the amount of phytoplankton available for other organisms, threaten native mussel populations, and accumulate contaminants within their tissues. (https://www.greatlakesnow.org/2020/02/zebra-mussels-impact-good-bad/)
Hexagenia spp.	Burrowing Mayfly	detritivore	Important food web link	The burrowing mayfly nymph eats decaying plant matter and is important in the transfer of energy from the detrital food chain to fishes, amphibians, reptiles, and birds in the Great Lakes ecosystem (https://www.pnas.org/content/pnas/early/2020/01/15/1913598117.full.pdf)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Gammarus fasciatus	Scud	benthic filter feeder	Locally abundant species	Potentially non-native; Gammarus fasciatus is an abundant member of benthic communities in the Great Lakes region and often aggregate amongst Dreissena colonies and areas of abundant detritus material (http://people.cst.cmich.edu/mcnau1as/zooplankton%20web/Gammarus/Gammarus.htm)
PLANT AND ALGAE				
Microcycstis aeruginosa	Cyanobacteria (blue-green algae)	Primary Producer	Important food web link; Nuisance species	*M. aeruginosa* is a widely distributed cyanobacteria that grows readily in nutrient-rich, slow-moving water. It is a nuisance species that forms harmful algal blooms (HAB) since it produces secondary toxic compounds ("microcystins)" that pose a danger to fish and wildlife and may impact to human recreational use due to exposure through direct contact, ingestion, or inhalation of water droplets. High levels of microcystin compounds lead to public beach closures.
PLANKTONIC				
Mysis relicta	Opossum Shrimp	Primary level	Locally abundant species; Thermal sensitive species; Important food web link	Primary food source for various sculpins, coregonids, and even burbot (source: http://people.cst.cmich.edu/mcnau1as/zooplankton%20web/Mysis/Mysis.html); Cold-water species that is adversely affected at temperatures > 15°C (EA 2008); established in all Great Lakes (https://www.glerl.noaa.gov/library/annual/2002/2002-04.pdf)
Diporeia spp.	Amphipod	Primary level	Important food web link	Important forage species in the offshore waters of the Lake Michigan food chain; recent changes in the condition, distribution, and abundance of several fish species have been attributed to the loss of Diporeia, including the commercially important lake whitefish (EA 2008)

Table 3-5. Thermal Tolerances of RIS for the Great Lakes Region

Species	Common Name	Life Stage	Acute			Life Stage	Chronic			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
FISH													
Esox lucius	Northern Pike	Eggs				Eggs	24.2		13	Eggs			
		Larvae				Larvae	20.6-28.5		13	Larvae			
		Juvenile				Juvenile	29-33		13	Juvenile			
		Adult				Adult	32-35.6	3-4.9	13	Adult	20	18.9	13
Salvelinus namaycush	Lake Trout	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile	22.5-23.5		10	Juvenile	12.1	7.2	13
		Adult				Adult	22.7-25.1		13	Adult	12.8	6.7	5
Morone chrysops	White Bass	Eggs				Eggs				Eggs			
		Larvae				Larvae	30-32	12.8	13	Larvae			
		Juvenile	35.3		13	Juvenile	33.5		13	Juvenile	31	27.8	13
		Adult				Adult	35		13	Adult	25	18	13
Micropterus dolomieu	Smallmouth bass	Eggs				Eggs				Eggs			
		Larvae				Larvae	30-33	10	13	Larvae			
		Juvenile	36.3		13	Juvenile	35	2-10	13	Juvenile	30	28	13
		Adult				Adult	35		13	Adult	31	15	13
Sander vitreus	Walleye	Eggs				Eggs				Eggs	19.4	16.7	20
		Larvae				Larvae				Larvae	21	15	20
		Juvenile	33-35		20	Juvenile	27-31.6		20	Juvenile	26	22	20
		Adult	34.4		20	Adult				Adult			

			Acute				Chronic				Optimal Thermal Range		
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
Perca flavescens	Yellow Perch	Eggs				Eggs				Eggs			
		Larvae	34.8-37.6		13	Larvae	26.5-33.3		10	Larvae			
		Juvenile	33.4		13	Juvenile	29.7		10	Juvenile			
		Adult	35		13	Adult	21.0-32.3		10	Adult	21.1	18.9	8
Lota lota	Burbot	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae	12	6	14
		Juvenile				Juvenile				Juvenile			
		Adult				Adult	23.3		13	Adult	21		12
Coregonus clupeaformis	Lake Whitefish	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae	16	12	13
		Juvenile				Juvenile	20.6-26.6		13	Juvenile	17		13
		Adult				Adult				Adult	15	3.5	13
Acipenser fulvescens	Lake Sturgeon	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	35.1		24	Juvenile				Juvenile			
		Adult				Adult				Adult	17.8	12.8	6
Coregonus hoyi	Bloater	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae	7	3.8	13
		Juvenile	27-29		13	Juvenile	22.2-26.7		13	Juvenile	14	11	13
		Adult				Adult	26-27		13	Adult	10	7	13

Species	Common Name	Life Stage	Acute			Life Stage	Chronic			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
Alosa pseudoharengus	Alewife	Eggs	35.6		1	Eggs	28		2	Eggs			
		Larvae	31		1	Larvae				Larvae	29	23	1
		Juvenile	31.9-34.4		13	Juvenile	26.5-32.1	3	13	Juvenile	20	15	1
		Adult	28.6-32	6-8	13	Adult				Adult	21	11	1
Ameiurus nebulosus	Brown Bullhead	Eggs				Eggs				Eggs			
		Larvae				Larvae	36.4-38.2		13	Larvae			
		Juvenile				Juvenile	35.6-36.5		13	Juvenile	31		13
		Adult	38		13	Adult	29-37.5		13	Adult	31	29	13
Pomoxis nigromaculatus	Black Crappie	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae	20	18	13
		Juvenile				Juvenile	33		13	Juvenile	25	22	13
		Adult	34.9		13	Adult	32.5-34		13	Adult	28.2	21	13
Cottus bairdi	Mottled Sculpin	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	30.4-33.8		13,20	Adult				Adult	22	16	21
Notropis hudsonius	Spottail Shiner	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile	37.3-38.1		10	Juvenile	28.5	20.1	13
		Adult	32.8		13	Adult	30.6-31.1		10	Adult	23.9	10	7

			Acute				Chronic				Optimal Thermal Range		
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
Dorosoma cepedianum	American Gizzard Shad	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	31	10.8-14.5	13	Juvenile	28.5		20	Juvenile			
		Adult				Adult	34-36.5		20	Adult	31	19	13,20
INVERTEBRATE													
Strophitus undulatus	Freshwater Mussel[2]	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile	28	26	16
		Adult	39-42.2		15	Adult				Adult			
Dreissena polymorpha	Zebra Mussel	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	33-36		25	Adult	30		25	Adult	25	20	26
Hexagenia spp.	Burrowing Mayfly	Eggs				Eggs				Eggs	34	31	18
		Larvae				Larvae	27.1	26.1	19	Larvae	20	15	28
		Juvenile				Juvenile				Juvenile	9.5		17
		Adult				Adult				Adult			
Gammarus fasciatus	Scud	Eggs				Eggs				Eggs			
		Larvae				Larvae	14.55		19	Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	34-35		9	Adult				Adult	15	10	9

Species	Common Name	Life Stage	Acute			Life Stage	Chronic			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
PLANT AND ALGAE													
Microcycstis aeruginosa	Cyanobacteria	NA	37	15	27	NA				NA	30	25	27
PLANKTONIC													
Mysis relicta	Opossum shrimp	NA	22		22	NA	20.5		22	NA	6-8		10
Diporeia spp.		NA				NA	28		23	NA			

[1] Numbers denote references found in Table 3-6

[2] Optimal temperature tolerances are based on the following species: *Epioblasma brevidens*, *Epioblasma capsaeformis*, and *Lampsilis fasciola.*

Table 3-6. List of References for RIS (Table 3-4 and Thermal Tolerances (Table 3-5)

Reference Number	Citation
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4	Becker, G. C. (1983). Fishes of Wisconsin.
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7	Minnesota Sea Grant. 10 Sep 2014. Spottail Shiner (Notropis hudsonius). http://www.seagrant.umn.edu/fisheries/profile/spottailshiner
8	Michigan Department of Natural Resources. 2015. Yellow Perch, Perca flavescens. https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82677---,00.html
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14	Mansfield, P. J., D. J. Jude, D. T. Michaud, D. C. Brazo, and J. Gulvas. (1983). Distribution and abundance of larval burbot and deepwater sculpin in Lake Michigan. Transactions of the American Fisheries Society, 112(2A), 162-172.

Reference Number	Citation
15	Galbraith, H. S., C. J. Blakeslee, and W. A. Lellis. (2012). Recent thermal history influences thermal tolerance in freshwater mussel species (Bivalvia: Unionoida). Freshwater Science 31(1): 83-92.
16	Carey, C. S., J. W. Jones, E. M. Hallerman, and R. S. Butler. (2013). Determining optimum temperature for growth and survival of laboratory-propagated juvenile freshwater mussels. North American Journal of Aquaculture, 75(4), 532-542.
17	Winter, A., J. J. Ciborowski, and T. B. Reynoldson. (1996). Effects of chronic hypoxia and reduced temperature on survival and growth of burrowing mayflies,(Hexagenia limbata)(Ephemeroptera: Ephemeridae). Canadian Journal of Fisheries and Aquatic Sciences, 53(7), 1565-1571.
18	Tennessen, K. J., and J. L. Miller. (1978). Effects of thermal discharge on aquatic insects in the Tennessee Valley (No. PB-295415). Tennessee Valley Authority, Muscle Shoals, AL (USA). Div. of Environmental Planning.
19	Gaufin, A. R. (1973). Water quality requirements of aquatic insects. For sale by the Supt. of Docs., USGPO.
20	Yoder, C. O., E. T. Rankin, and B. J. Armitage. (2006). Re-evaluation of the technical justification for existing Ohio River mainstem temperature criteria. Report to Ohio River Valley Water Sanitation Commission. Tech. Rept. MBI/05-05-2. Columbus, OH. 56 pp.+ 4 appendices.
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22	DeGraeve, G. M., and J. B. Reynolds. (1975). Feeding behavior and temperature and light tolerance of Mysis relicta in the laboratory. Transactions of the American Fisheries Society, 104(2), 394-397.
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3.4 Middle Atlantic Representative Important Species (RIS) Temperature Tolerance Data

Table 3-7 identifies 28 RIS for use in thermal studies in the Middle Atlantic region, segregated into 16 marine/estuarine and 12 freshwater species. EPA used several regional sources including the 1978 316(a) Demonstration Study for the Indian Point Generating Station (Hudson River, NY), a report from the Chesapeake Executive Council (1988) that describes target species for the Chesapeake Bay, and several Middle Atlantic states' watershed inventories to identify candidate RIS for this region. From these candidate species, EPA selected species to include species with several trophic levels, commercial and/or recreational value, ecological functions,[15] or special status/sensitivity. EPA then confirmed availability of good quality thermal sensitivity limit data for these species before finalizing the list.

The final list of RIS for marine and estuarine waters in Table 3-7 included the following fish species: striped bass (*Morone saxatilis*), white perch (*Morone americana*), Atlantic sturgeon (*Acipenser oxyrhynchus*), shortnose sturgeon (*Acipenser brevirostrum*), alewife (*Alosa pseudoharengus*), bay anchovy (*Anchoa mitchilli*), American shad (*Alosa sapidissima*), spot (*Leiostomus xanthurus*), and Atlantic menhaden (*Brevoortia tyrannus*). Together, these species represent the full array of RIS criteria described in Section 3.1. To this list of fish, EPA added the eastern oyster (*Crassostrea virginica*) and blue crab (*Callinectes sapidus*) to represent invertebrates, eelgrass (*Zostera marina*) and widgeongrass (*Ruppia maritima*) to represent aquatic plants, common carp (*Cyprinus carpio*) to represent nuisance species, and *Acartia tonsa* (a copepod) and *Prorocentrum minimum* (a dinoflagellate) to represent zooplankton and phytoplankton, respectively.

The list of freshwater RIS included several fish species that could be found in mainstem and tributary waterbodies: smallmouth bass (*Micropterus dolomieu*), yellow perch (*Perca flavescens*), brook trout (*Salvelinus fontinalis*), pumpkinseed (*Lepomis gibbosus*), white sucker (*Catostomus commersonii*), common shiner (*Luxilus cornutus*), and fantail darter (*Etheostoma flabellare*). EPA also included several marine/estuarine RIS that are often present in freshwaters (e.g., white perch, alewife, and common carp). EPA also included a freshwater mussel (*Elliptio complanata*) and the common crayfish (*Cambarus bartonii*) to represent invertebrates, clasping-leaf pondweed (*Potamogeton perfoliatus*) to represent aquatic plants, and the cladoceran *Daphnia spp.* (water flea) and *Microcystis aeruginosa* (a nuisance blue-green algal bloom former) to represent zooplankton and phytoplankton, respectively.

3.4.1 RIS Thermal Tolerances

As part of the selection process for the RIS for the Middle Atlantic region, EPA investigated sources of thermal tolerance data. Table 3-8 provides the data that were found. Two reports from the Chesapeake Bay Program (Chesapeake Executive Council [1988], Funderburk [1991]) provided habitat requirements, temperature tolerances, and optimal temperature ranges for many of the selected marine and estuarine species. Additionally, EPA searched several government agency websites for habitat requirement and thermal tolerance reports. The Species Profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates series published by the USFWS (e.g., Rogers and Van Den Avyle [1989]) summarizes available thermal tolerance data for many of the selected species. For freshwater species,

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[7] The role and feeding type of a RIS can vary widely during its life cycle. For assignment of trophic level and feeding model, the adult stage was used.

the compilations of Wismer and Christie (1987), Beitinger et al. 2000a, and Yoder (Yoder et al. 2006; Yoder 2012) were consulted, among others. Thermal tolerance data were also available in reports from the EPA, the U.S. Department of Commerce, and other sources.

3.4.2 Assumptions and Uncertainty

This section provides useful information to applicants and permit writers selecting RIS for thermal mixing zone and 316(a) demonstration studies in the Middle Atlantic. However, use of the data is subject to important assumptions and sources of uncertainty, including:

- Documented thermal limits come from many sources (some quite dated). While all sources of thermal limit data were treated equally, there are likely to be methodological differences between studies due to laboratory conditions, rearing practices, and condition/source of test organisms.
- Thermal limits were not available for all species' life stages and the identified value may or may not represent the most thermally sensitive life stage.
- In some cases, a surrogate species was used to estimate an RIS thermal limit.
- Selected RIS may not be representative of local species due to site-specific factors or because RIS life stages may only be present in certain habitat areas (e.g., spawning beds, nursery areas).
- Thermal limits represent one type of physical stress on the organism. In the field, species are likely to be subject to other natural (food availability, lack of refuge areas) and anthropogenic (pollution, entrainment) stressors that could affect thermal tolerance.

These sources of uncertainty should be considered on a site-specific basis. When considering relative uncertainty among regions, the assumptions and uncertainties applicable to RIS in the Middle Atlantic region are likely to be similar to those uncertainties and assumptions that must be made for other geographic regions.

Table 3-7. List of Selected RIS for Middle Atlantic Region

Species	Common Name	Trophic Status	RIS Status	RIS Justification
MARINE AND ESTUARINE SPECIES				
FISH				
Morone saxatilis	Striped bass	T-3 piscivore	Commercial and recreational value; Locally abundant species	The striped bass is Maryland's state fish, and one of the most popular commercial and recreational catches in the Chesapeake Bay. The Bay is the largest striped bass nursery area on the Atlantic coast. Seventy to 90 percent of the Atlantic striped bass population uses the Bay to spawn. (http://www.chesapeakebay.net/fieldguide/critter/striped_bass)
Morone americana	White perch	T-3 piscivore	Commercial and recreational value; Locally abundant species	Indicators of environmental stress; commercially and recreationally important species. White perch are a resident species and a good indicator of toxic contaminant concentrations in the Bay's waters. (http://www.chesapeakebay.net/blog/post/white_perch_in_the_bay_and_its_rivers)
Cyprinus carpio	Common carp	T-2 omnivore	Nuisance species	Although common carp was a popular food fish in the early 1980s, it fell into disfavor soon after and is now considered a nuisance fish because of its abundance and detrimental effects on aquatic habitats. (http://nas.er.usgs.gov/queries/factsheet.aspx?speciesID=4)
Acipenser brevirostrum	Shortnose sturgeon	T-2 omnivore	Rare, threatened or endangered species	Endangered Species. Lives mostly in the Potomac and Susquehanna river; sturgeon is very sensitive to low oxygen, pollution and other poor water conditions. This, combined with their slow rate of maturity, loss of spawning grounds and historic commercial fishing pressure, has caused the species to become very rare. (http://www.chesapeakebay.net/fieldguide/critter/shortnose_sturgeon)
Acipenser oxyrhynchus	Atlantic sturgeon	T-2 omnivore	Commercial and recreational value; Rare, threatened or endangered species	Endangered species. Sturgeons are very sensitive to low oxygen, pollution and other poor water conditions. This, combined with their slow rate of maturity, loss of spawning grounds, and historic commercial fishing pressure, has caused the species to become very rare. (http://www.chesapeakebay.net/fieldguide/critter/atlantic_sturgeon)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Alosa sapidissima	American shad	T-1 planktivore	Commercial and recreational value; Important food web link; Locally abundant species	American shad are the most well-known river herring in the Chesapeake Bay and are critical to the structure and function of the ecological system. Shad once supported the most valuable finfish fishery in the region, but pollution, historic overfishing and loss of spawning grounds have lowered shad populations. Commercial shad harvest is now closed across most of the region. (http://www.chesapeakebay.net/issues/issue/shad)
Leiostomus xanthurus	Spot croaker	T-1 planktivore	Commercial and recreational value; Locally abundant species	Recreationally important and numerically abundant or prominent in the system (Spot are also called Norfolk spot). They are one of the most abundant fish in the Chesapeake Bay. (http://www.chesapeakebay.net/fieldguide/critter/spot)
Brevoortia tyrannus	Atlantic menhaden	T-1 planktivore	Commercial and recreational value; Important food web link	Atlantic menhaden are critical to Middle Atlantic ecosystems, filtering pollutants out of the water and forming an important link in the food web. Menhaden also support one of the oldest commercial fisheries on the Atlantic coast. (http://www.chesapeakebay.net/issues/issue/menhaden#inline)
Alosa pseudoharengus	Alewife	T-2 omnivore	Commercial and recreational value; Locally abundant species; Important food web link	Commercially important. The "river herring" fishery (which includes the alewife and the blueback herring) has been one of the most valuable in the Bay. The degradation and destruction of spawning habitat and the restriction of spawning migration (or fish passage) by dams have contributed to the decline of these stocks. (http://www.chesapeakebay.net/fieldguide/critter/alewife)
Anchoa mitchilli	Bay anchovy	T-1 planktivore	Commercial and recreational value; Locally abundant species; Important food web link	Bay anchovies are the most abundant and commonly found fish in the Chesapeake Bay. These fish are highly intolerant of low oxygen conditions, and are particularly sensitive to low-oxygen "dead zones." Anchovies are economically important as a species used for fish oil and fishmeal. (http://www.chesapeakebay.net/fieldguide/critter/bay_anchovy)
INVERTEBRATES				
Crassostrea virginica	Eastern oyster	Benthic filter feeder	Commercial and recreational value; Habitat formers	Oysters are one of the most important commercial catches in the Chesapeake Bay. (http://www.chesapeakebay.net/fieldguide/critter/eastern_oyster)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Callinectes sapidus	Blue crab	Benthic omnivore	Commercial and recreational value; Important food web link	Prominent in the system; commercially and recreationally important. Chesapeake Bay's signature crustacean is one of the most recognizable species in the watershed, and supports commercial and recreational fisheries. But blue crabs are vulnerable to pollution, habitat loss and harvest pressure, and their abundance has fluctuated over time. (http://www.chesapeakebay.net/issues/issue/blue_crabs)
PLANTS				
Zostera marina	Eelgrass	Primary Producer	Habitat formers; Important food web link; Thermal sensitive species	Sensitive to environmental stressors, including thermal stressors. Their abundance is a good indicator of Bay health; Some bay grass species, including eelgrass, cannot grow in water that is too warm. In 2005, high temperatures caused large beds of eelgrass in the lower Chesapeake Bay to die. It can take several years for bay grass beds to recover from these kinds of large-scale losses. (http://www.chesapeakebay.net/issues/issue/bay_grasses#inline)
Ruppia maritima	Widgeongrass	Primary Producer	Habitat formers; Important food web link	Wigeongrass and its detritus provide food and cover for a large invertebrate biota, although direct consumption of the living plants is minimal. Wigeongrass beds in coastal wetlands are heavily used by fish. The plant is recognized worldwide as an important food of migrant and wintering waterfowl, wading birds, and shorebirds. (U.S. FWS 1991)
PLANKTONIC				
Acartia tonsa	copepod	Primary Level	Important food web link; Locally abundant species	The most abundant copepod found in zooplankton monitoring survey (Grant and Olney 1983; http://www.vims.edu/GreyLit/VIMS/ssr115.pdf); important food source for menhaden, spot, and many juvenile fish (http://animaldiversity.org/accounts/Acartia_tonsa/); abundance started to decline after long-term rise in water temperature. (Kimmel, Boynton, and Roman 2012)
Prorocentrum minimum	dinoflagellate	Primary Producer	Important food web link; Nuisance species	*P. minimum* is a toxic species; it produces venerupin (hepatotoxin) which has caused shellfish poisoning resulting in gastrointestinal illnesses in humans and a number of deaths. This species is also responsible for shellfish kills in Japan and the Gulf of Mexico, Florida. (http://species-identification.org/species.php?species_group=dinoflagellates&id=93)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
FRESHWATER SPECIES				
FISH				
Micropterus dolomieu	Smallmouth bass	T-3 piscivore	Commercial and recreational value; Locally abundant species	Smallmouth bass are originally from the Mississippi River basin and Great Lakes. They favor faster-moving, rocky, cooler, upstream sections of rivers; eat crayfish, insect larvae, and other fish. They spawn in rocky areas of rivers during May and June. Predators of smallmouth include walleye, kingfishers, eagles, osprey, and humans. Young smallmouth are preyed upon by older, larger smallmouth. (https://www.chesapeakebay.net/S=0/fieldguide/critter/smallmouth_bass)
Perca flavescens	Yellow Perch	T-3 piscivore	Commercial and recreational value; Important food web link; Locally abundant species	The yellow or ringed perch is one of the most important food fishes of the Middle Atlantic states. Yellow Perch live in a variety of aquatic habitats, including warm or cool lakes, ponds and sluggish streams. Young perch feed on zooplankton and small aquatic insects, and in turn are food for larger predator fish. Small fish, including small perch, are mainstays of the adult perch's diet. Adult perch also eat aquatic insects and crustaceans. (https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/YellowPerch.aspx)
Salvelinus fontinalis	Brook Trout	T-2 omnivore	Commercial and recreational value; Thermal sensitive species	The Brook Trout's original home was northeastern North America, through the Great Lakes, and south along the Appalachian Mountains to Georgia. The Brook Trout lives naturally in small, cold, clean streams. It also adapts to ponds and lakes, as well as instream beaver ponds. Trout feed on aquatic and terrestrial insects, crustaceans and small fish. Brook Trout can tolerate relatively acidic waters, but not temperatures much over 65° F. (https://www.wildlife.state.nh.us/fishing/profiles/brook-trout.html)
Lepomis gibbosus	Pumpkinseed	T-2 omnivore	Commercial and recreational value; Important food web link; Locally abundant species	Pumpkinseeds are found throughout Pennsylvania, and in eastern Canada and the eastern United States in the Atlantic watershed and upper Mississippi watershed. Pumpkinseeds are found in the quiet, weedy shallows of streams, lakes and ponds. They usually live in cooler water than other sunfish. They can tolerate poorer water quality, surviving periods of low oxygen. They also tolerate muddy water and acidic water. Pumpkinseeds feed mostly on the bottom of a stream or pond, where they also eat burrowing and other aquatic insects, as well as snails, for which they have evolved special throat structures. (https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/Pumpkinseed.aspx).

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Catostomus commersonii	White sucker	T-2 omnivore	Important food web link; Locally abundant species	White suckers are found throughout the northeast and Midwest US and can be found in small and large streams, ponds, lakes, and reservoirs. They prefer deeper water in fall and winter months but move into shallow water in lakes and riffle areas in streams. They can withstand a wide variety of conditions including turbidity and low oxygen levels. Larval white suckers feed on protozoans, diatoms, and small crustaceans. Adults are bottom fish and eat mud, plants, mollusks, insects, diatoms, crustaceans, and protozoans. (https://www.nrc.gov/docs/ML0708/ML070800423.pdf)
Luxilus cornutus	Common shiner	T-2 omnivore	Important food web link; Locally abundant species	The common shiner is found across southern Canada to Saskatchewan, and south to Kansas and Missouri in the Ohio and Mississippi River watersheds and in the Atlantic Coast states to Virginia's James River. It is an important component for the food web in Pennsylvania stream ecosystems. It prefers streams of small to moderate size that are shaded with cool and clear water. The common shiner is omnivorous and feeds on insects and aquatic vegetation. (https://www.fishandboat.com/Fish/PennsylvaniaFishes/GalleryPennsylvaniaFishes/Pages/CarpsandMinnows.aspx)
Etheostoma flabellare	Fantail darter	T-2 omnivore	Important food web; Thermal sensitive species	This species occurs from southern Minnesota and Wisconsin, east through the southern Great Lakes to southern Quebec and New York State. Fantail darters occur in riffle areas of streams where there are cobbles and gravel. The diet consists of a variety of insects, cladocerans, amphipods, isopods, hydrachnids, and gastropods. (http://www2.dnr.cornell.edu/cek7/nyfish/Percidae/fantail_darter.html)
INVERTEBRATES				
Elliptio complanata	Freshwater Mussel	Benthic filter feeder	Habitat formers; Important food web link; Thermal sensitive species	Freshwater mussels are found across the U.S. In good habitat, mussels will form dense concentrations called mussel beds, which can contain thousands of individuals sometimes representing dozens of species. Mussels are food for fish, raccoons, river otters, mink and muskrats, and mussel beds create habitat for many other invertebrates. Because mussels release unwanted food items in a mucus strand, they transfer suspended food from the water column to the stream bed, making this food available for aquatic insects and other small animals. As filter feeders, they clean harmful bacteria and parasites from the water. (http://molluskconservation.org/MUSSELS/Habitat.html)

Species	Common Name	Trophic Status	RIS Status	RIS Justification
Cambarus bartonii	Common Crayfish	Benthic omnivore	Important food web link	Common crayfish consume dead animal and plant matter from the bottom of streams. They also control populations of insects and other animals are a common food source for many predators. (https://animaldiversity.org/accounts/Cambarus_bartonii/)
PLANTS AND ALGAE				
Potamogeton perfoliatus	Claspingleaved Pondweed	Submersed aquatic plant	Habitat formers; Important food web link	*Potamogeton perfoliatus* is a submerged aquatic plant that occurs in still and flowing freshwaters in temperate climates. This is one of the commonest Potamogeton species. It is common in lakes, ditches and slow rivers and streams, and is tolerant of quite a wide range of nutrient status. (http://www.issg.org/database/species/ecology.asp?si=902&fr=1&sts=tss&lang=EN)
PLANKTONIC				
Daphnia species	Copepod	Primary Consumer	Important food web link; Locally abundant species	*Daphnia* species inhabit most types of standing freshwater except for extreme habitats, such as hot springs. All age classes are good swimmers and are mostly pelagic. They are usually suspension feeders (filter feeders) but some species are associated with substrates such as water plants or the bottom sediments of shallow ponds. Adults range from less than 1 mm to 5 mm in size, with the smaller species typically found in ponds or lakes with fish predation. (https://www.ncbi.nlm.nih.gov/books/NBK2042/)
Microcycstis aeruginosa	Cyanobacteria (blue-green algae)	Primary Producer	Important food web link; Nuisance species	*M. aeruginosa* is a widely distributed cyanobacteria that grows readily in nutrient-rich, slow-moving water. It is a nuisance species that forms HABs since it produces secondary toxic compounds ("microcystins") that pose a danger to fish and wildlife and may impact to human recreational use due to exposure through direct contact, ingestion, or inhalation of water droplets. High levels of microcystins compounds lead to public beach closures. (https://www.michigan.gov/egle/0,9429,7-135-3313_3681_3686_3728-383630--,00.html#3)

Table 3-8. Thermal Tolerances of RIS for the Middle Atlantic Region

			Acute				Chronic (°C)				Optimal Thermal Range		
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
MARINE AND ESTUARINE SPECIES													
FISH													
Morone saxatilis	Striped bass	Eggs	23-27	11-12	3	Eggs				Eggs			
		Larvae	28.9-		3	Larvae		10	3	Larvae	21	18	3
		Juvenile				Juvenile				Juvenile	26	20	3
		Adult	31.6		4	Adult	25		3	Adult	22	20	3
Morone americana	White Perch	Eggs				Eggs				Eggs	14	11	30
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile	31	15.2	30
		Adult	33-35.5		29	Adult				Adult	32.2	21.5	30
Cyprinus carpio	Common Carp	Eggs	40.6		35	Eggs	31-35		35	Eggs			
		Larvae				Larvae	36-39		35	Larvae			
		Juvenile				Juvenile				Juvenile	32		35
		Adult	38-39		35	Adult	31-36		35	Adult	30	20	35
Acipenser brevirostrum	Shortnose sturgeon	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	34.8-		10	Adult	28.2-		10	Adult	28.3	26.2	10
Acipenser oxyrhynchus	Atlantic sturgeon	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult				Adult	28		11	Adult	24	12	12
Alosa sapidissima	American shad	Eggs	32.5-34		20	Eggs	27	8-10	20	Eggs		17	20
		Larvae	33.5		20	Larvae				Larvae	26.5	15.5	20
		Juvenile	30-35	2.2	20	Juvenile		4-6	20	Juvenile	23.9	15.6	20
		Adult				Adult				Adult			
Leiostomus xanthurus	Spot croaker	Eggs		14	17	Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	30-40	4-5	16	Juvenile				Juvenile	20	6	17
		Adult	31		15	Adult	35.2		16	Adult			

			Acute				Chronic (°C)				Optimal Thermal Range		
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
Brevoortia tyrannus	Atlantic menhaden	Eggs				Eggs				Eggs			
		Larvae				Larvae		3	7	Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	33		6	Adult				Adult	20	15	7
Alosa pseudoharengus	Alewife	Eggs	35.6		13	Eggs	28		14	Eggs			
		Larvae	31		13	Larvae				Larvae	29	23	13
		Juvenile	26.5-		13	Juvenile	30-31	7	13	Juvenile	20	15	13
		Adult	29.8-	6-10.5	13	Adult				Adult	21	11	13
Anchoa mitchilli	Bay anchovy	Eggs				Eggs				Eggs	30	13	5
		Larvae				Larvae				Larvae	30	15	5
		Juvenile				Juvenile				Juvenile	30	10	5
		Adult	40		5	Adult				Adult	32.2	8.1	5
INVERTEBRATE													
Crassostrea virginica	Eastern oyster	Eggs				Eggs				Eggs			
		Larvae	45		8	Larvae				Larvae	32.5	30	8
		Juvenile				Juvenile				Juvenile			
		Adult				Adult	32	6-7	8	Adult	30	20	8
Callinectes sapidus	Blue Crabs	Eggs				Eggs				Eggs			
		Larvae				Larvae	30	21	19	Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	37-39	4.6-6	18	Adult	30	13	19	Adult			
PLANT AND ALGAE													
Zostera marina[2]	Eelgrass	NA	32		22	NA	25-30		23-25, 44	NA	20	10	25
Ruppia maritima	Widgeongrass	NA	40		28	NA	30		28	NA	29	18	28
PLANKTONIC													
Acartia tonsa	copepod	NA	41-46.3		32	NA	37		32	NA	25	17	31
Prorocentrum	dinoflagellate	NA				NA				NA	28	12	34

Species	Common Name	Life Stage	Acute			Life Stage	Chronic (°C)			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
FRESHWATER SPECIES													
FISH													
Micropterus dolomieu	Smallmouth bass	Eggs				Eggs				Eggs			
		Larvae				Larvae	30-33	10	35	Larvae			
		Juvenile	36.3		35	Juvenile	35	2-10	35	Juvenile	30	28	35
		Adult				Adult	35		35	Adult	31	15	35
Perca flavescens	Yellow Perch	Eggs				Eggs				Eggs			
		Larvae				Larvae	26.5-		37	Larvae			
		Juvenile				Juvenile	29.7		37	Juvenile	23.3	20	46
		Adult				Adult	21-32.3		37	Adult	20.1	17.6	46
Salvelinus fontinalis	Brook Trout	Eggs				Eggs				Eggs			
		Larvae				Larvae	20.1		35	Larvae			
		Juvenile				Juvenile	24-25.8		35	Juvenile			
		Adult	28.7-		4	Adult				Adult	15.6	13.9	36
Lepomis gibbosus	Pumpkinseed	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile	30.5-	5.9	35	Juvenile			
		Adult	35.1-		35	Adult	31.6-	5.9-	35	Adult	30.3	25.3	35
Catostomus commersonii	White sucker	Eggs				Eggs				Eggs			
		Larvae	32.7		35	Larvae	28.3-		35	Larvae			
		Juvenile	35.1	36.1	35	Juvenile	30.0-		35	Juvenile			
		Adult	31.6		35	Adult				Adult	27	19	35
Luxilus cornutus	Common shiner	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	35.7		4	Adult	26.7-	3.7-7.8	35	Adult	21.9	11.8	38, 47
Etheostoma flabellare	Fantail darter	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile			
		Adult	32.1		35	Adult				Adult	19.3-		39

Species	Common Name	Life Stage	Acute			Life Stage	Chronic (°C)			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
INVERTEBRATES													
Elliptio complanata	Freshwater Mussel[3]	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile	28	26	45
		Adult	40-42.7		21	Adult				Adult			
Cambarus bartonii	Common Crayfish	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile	32.5		40	Juvenile			
		Adult				Adult	33.8		40	Adult			
PLANTS													
Potamogeton perfoliatus	Clasping-leaf Pondweed	NA	45		43	NA				NA			
PLANKTONIC													
Daphnia magna	Cladoceran	NA	39.4		41	NA	34.8		41	NA			
Microcystis aeruginosa	HAB-forming cyanobacter	NA	37	15	42	NA				NA	30	25	42

[1] Numbers denote references found in Table 3-9.

[2] *Zostera mueller* used surrogate for acute temperature only.

[3] Optimal temperature tolerances based on the following species: *Epioblasma brevidens*, *Epioblasma capsaeformis*, and *Lampsilis fasciola*.

Table 3-9. List of References for RIS (Table 3-7) and Thermal Tolerances (Table 3-8)

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3.5 Inland Great Rivers Representative Important Species (RIS) Temperature Tolerance Data

Table 3-10 identifies 15 RIS for use in thermal studies in the Inland Great Rivers region. EPA used several regional sources to identify candidate RIS for this region, including the 316(a) demonstrations for several facilities (i.e., Westinghouse Environmental Systems Department (WESD) 1975 (Clifty Creek Nuclear Station); Commonwealth Edison (ComEd) 1980 (Dresden Nuclear Station); Dairyland Power Cooperative 1982 (John P. Madgett Steam Electric); and HDR Engineering, Inc. 2009 (Quad Cities Nuclear Station, or "QCNS") and several Inland Great Rivers states' watershed inventories. From these candidate species, EPA selected species to include several trophic levels, species with commercial and/or recreational value, species with key ecological functions,[16] or special status/sensitivity. EPA then confirmed availability of good quality thermal sensitivity limit data for these species before finalizing the list.

The list of RIS for Inland Great Rivers waters in Table 3-10 included several fish species: channel catfish (*Ictalurus punctatus*), smallmouth bass (*Micropterus dolomieu*), walleye (*Sander vitreus*), white bass (*Morone chrysops*), freshwater drum (*Aplodinotus grunniens*), golden redhorse (*Moxostomata erythrurum*), shovelnose sturgeon (*Scaphirhynchus platorynchus*), emerald shiner (*Notropis atherinoides*), smallmouth buffalo (*Ictiobus bubalus*), and American paddlefish (*Polyodon spathula*). To this list of fish, EPA added two native freshwater mussel species (*Megalonaias nervosa* and *Strophitus undulatus*), and burrowing mayfly (*Hexagenia spp.*) to represent invertebrates, wild celery (*Vallisneria americana)* to represent aquatic plants, and cyanobacteria (*Microcycstis aeruginosa*) for planktonic species. Together, these species represent the full array of RIS criteria described in Section 3.1.

3.5.1 RIS Thermal Tolerances

As part of the selection process for the RIS for the Inland Great Rivers region, EPA investigated sources of thermal tolerance data. Table 3-11 provides the data that were found. The Quad Cities 316(a) study (HDR Engineering, Inc. 2009) and the thermal data compilations of Wismer and Christie (1987), Beitinger et al. (2000a), and Yoder (Yoder et al. 2006; Yoder 2012) provided temperature tolerances for many of the selected species. Additionally, EPA searched several government agency websites for habitat requirement and thermal tolerance reports. Thermal tolerance data were also available in reports from the EPA, the U.S. Department of Commerce, and other sources.

3.5.2 Assumptions and Uncertainty

This section provides useful information to applicants and permit writers selecting RIS for thermal mixing zone and 316(a) demonstration studies in the Inland Great Rivers. However, use of the data is subject to important assumptions and sources of uncertainty, including:

- Documented thermal limits come from myriad sources (some quite dated). While all sources of thermal limit data were treated equally, there are likely to be methodological differences between studies due to laboratory conditions, rearing practices, and condition/source of test organisms.

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[16] The role and feeding type of a RIS can vary widely during its life cycle. For assignment of trophic level and feeding model, the adult stage was used.

- Thermal limits were not available for all species' life stages and the identified value may or may not represent the most thermally sensitive life stage.
- In some cases, a surrogate species was used to estimate an RIS thermal limits.
- Selected RIS may not be representative of local species due to site-specific factors or because RIS life stages may only be present in certain habitat areas (e.g., spawning beds, nursery areas).
- Thermal limits represent one type of physical stress on the organism. In the field, species are likely to be subject to other natural (food availability, lack of refuge areas) and anthropogenic (pollution, entrainment) stressors that could affect thermal tolerance.

These sources of uncertainty should be considered on a site-specific basis. When considering relative uncertainty among regions, the assumptions and uncertainties applicable to RIS in the Inland Great Rivers region are likely to be similar to those uncertainties and assumptions that must be made for other geographic regions.

Table 3-10. List of Selected RIS for Inland Great Rivers Region

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
FISH				
Micropterus dolomieu	Smallmouth Bass	T-3 piscivore	Commercial and recreational value	Smallmouth bass are important predator fish and are one of the top game and food fish. It is a member of the warm-water guild living in Mississippi River and is representative of several popular recreational species including bluegill, pumpkinseed, and green sunfish. (https://www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614_82601---,00.html)
Sander vitreus	Walleye	T-3 piscivore	Commercial and recreational value	The Walleye is the largest member of the perch family, attaining weights of over 20 pounds. Its size, sporting qualities and delicious flesh make it one of the most important game species in North America (http://www.iowadnr.gov/Fishing/Iowa-Fish-Species/Fish-Details/SpeciesCode/WAE)
Ictalurus punctatus	Channel Catfish	T-3 pred/omniv	Commercial and recreational value; Locally abundant species	An important recreational and commercial species in the Mississippi River and representative of a large number of temperature-tolerant temperate species, including: black bullhead, common carp, bigmouth buffalo, longnose gar, gizzard shad, and freshwater drum. It is a predator species [2]) and one of the ten most abundant species in the Ohio River between 1957 and 1980. [3]
Morone chrysops	White Bass	T-2 omnivore	Commercial and recreational value	Primary recreational species of interest [2]; One of the most important game fish in Missouri's large impoundments (http://mdc.mo.gov/discover-nature/field-guide/white-bass)
Aplodinotus grunniens	Freshwater Drum	T-2 omnivore	Commercial and recreational value; Locally abundant species	One of the ten most abundant species in the Ohio River between 1957 and 1980 [3]; commercially and recreationally important - accounted for 5.4% of all commercial harvests in the Upper Mississippi River Basin 1989 to 2005. [1]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
Moxostoma erythrurum	Golden redhorse	T-2 omnivore	Commercial and recreational value; Locally abundant species	A common benthic feeder widely distributed and an occasional sport fish (gigging). There are populations located in the drainage basins of the Mississippi River, Ohio River, and the lower Missouri River. It occurs in pools and riffles of moderately clear permanent streams with moderate siltation, moderate current, and gravel or rocky bottoms. Feeds on immature mayflies, caddisflies and midges. [13, 21]
Scaphirhynchus platorynchus	Shovelnose Sturgeon	T-2 omnivore	Rare, threatened or endangered species; Commercial and recreational value	Listed as vulnerable on the IUCN list (http://www.iucnredlist.org/details/19943/0); permitted sport fish, but because it closely resembles the pallid sturgeon (which is in danger of becoming extinct, the shovelnose sturgeon is illegal to harvest for commercial purposes in Missouri; the most abundant sturgeon in the Missouri and Mississippi Rivers (http://mdc.mo.gov/discover-nature/field-guide/shovelnose-sturgeon)
Notropis atherinoides	Emerald shiner	T-2 omnivore	Locally abundant species	One of the common Mississippi River species that consistently dominates fish collections [2]. The most common minnow collected by the Ohio River Valley Water Sanitation Commission (ORSANCO) between 1990-2015 on the length of the 981-mile-long Ohio River. [19,23]
Ictiobus bubalus	Smallmouth Buffalo	T-2 omnivore	Commercial and recreational value; Locally abundant species	Commercially and recreationally important [1]; common species in the Mississippi and Ohio Rivers. [2, 20].
Polyodon spathula	American Paddlefish	T-1 planktivore	Commercial and recreational value	People consume paddlefish meat and roe (caviar). The worldwide protection of sturgeon species is expected to have a dramatic impact on commercial paddlefish harvest by creating a greater demand for paddlefish caviar. It has declined throughout its range due to habitat loss and over-harvest. Competition from invasive species, such as silver and big head carp, is a potential serious threat to paddlefish. [2]

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
INVERTEBRATE				
Strophitus undulatus	Freshwater Mussel	filter feeder	Habitat formers; Important food web link	This species is common on the Atlantic Slope drainages and the smaller rivers in the inland rivers region. Mussels are food for fish, raccoons, river otters, mink and muskrats, and mussel beds actually create habitat for many other invertebrates. Because mussels release unwanted food items in a mucus strand, they transfer suspended food from the water column to the stream bed, making this food available for aquatic insects and other small animals. As filter feeders, they clean harmful bacteria and parasites from the water. (https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_054084.pdf)
Megalonaisas nervosa.	Washboard mussel	Filler feeder	Habitat formers; Important food web link	The washboard mussel is a large river species historically found in the Ohio, Mississippi and Missouri River drainages. The washboard is typically a large river species, inhabiting the main channel areas of a stream. Suitable habitat consists of slow current areas with substrates composed of sand, gravel, or mud. Host fishes for the glochidia of the washboard have been verified as the green sunfish (*Lepomis cyanellus*), black bullhead (*Ameiurus melas*), and the channel catfish (*Ictalurus punctatus*) (https://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=IMBIV29020)
Hexagenia spp.	Burrowing Mayfly	detritivore	Important food web link	Hexagenia nymphs are aquatic and dig u-shaped burrows in the sediment at the bottom of lakes and streams in temperate habitats. The most suitable habitats for these nymphs have well-mixed, shallow water about 3 meters deep, which ensures the aeration of sediment and abundant detritus for food. At sampling stations in the Mississippi River in 1958, *Hexagenia* spp. comprised over 50 percent by volume of the food of channel catfish, freshwater drum, mooneyes, goldeneyes, and white bass,

Species	Common Name	Trophic Status	RIS Status	RIS Justification[1]
				and over 40 percent of the food of paddlefish and white crappies. These mayfly naiads were also eaten by shovelnose sturgeon. [5]
PLANT				
Vallisneria americana	Wild Celery	primary producer	Habitat formers; Important food web link	The most dominant submersed plant in much of the Mississippi River in the 1960s; wild celery and other submersed aquatic plants significantly declined between 1987 and 1989 and continued to decline through 1994; wild celery is a critical component of quality waterfowl staging areas. Wild celery improves water quality by stabilizing sediments, filtering suspended materials, and absorbing nutrients such as phosphorus. Wild celery offers shelter and support for invertebrate populations (http://gis.smumn.edu/GradProjects/SeitzA.pdf)
PLANKTONIC				
Microcystis aeruginosa	cyanobacteria	HAB form, primary producer	Important food web link; Nuisance species	In recent study in the Upper Mississippi River [6], Cyanobacteria were present in 204 of 224 samples (96%). In addition, 1 in every 10 of samples could be classified as having a moderate to severe cyanobacteria bloom.

[1] Numbers in brackets denote references found in Table 3-12.

Table 3-11. Thermal Tolerances of RIS for the Inland Great Rivers Region

			Acute				Chronic				Optimal Thermal Range		
Species	Common Name	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]	Life Stage	Upper (°C)	Lower (°C)	Refs.[1]
FISH													
Micropterus dolomieu	Smallmouth Bass	Eggs				Eggs				Eggs			
		Larvae				Larvae	30-33	10	13	Larvae			
		Juvenile	36.3		13	Juvenile	35	2-10	13	Juvenile	30	28	13
		Adult				Adult	35		13	Adult	31	15	13
Sander vitreus	Walleye	Eggs				Eggs				Eggs	19.4	16.7	13
		Larvae				Larvae				Larvae	21	15	13
		Juvenile	33-35		13	Juvenile	27-31.6		13	Juvenile	26	22	13
		Adult	34.4		13	Adult				Adult			
Ictalurus punctatus	Channel Catfish	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	34.5-42.5		13	Juvenile	32.7-33.5		13	Juvenile	29.7	17	13
		Adult				Adult	35-38		13	Adult	32	25	13
Morone chrysops	White Bass	Eggs				Eggs				Eggs			
		Larvae				Larvae	30-32	12.8	14	Larvae			
		Juvenile	35.3		14	Juvenile	33.5		14	Juvenile	31	27.8	14
		Adult	35.3		13	Adult	35		14	Adult	30.2	25.5	13
Aplodinotus grunniens	Freshwater Drum	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	34		13	Juvenile	32.8		13	Juvenile			
		Adult				Adult	30.6		13	Adult	22.2	21.6	13
Moxostoma erythrurum	Golden Redhorse	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	35.4		13	Juvenile				Juvenile			
		Adult	35.4		13	Adult				Adult	27.5	26	13

			Acute				Chronic				Optimal Thermal Range		
Species	**Common Name**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**	**Life Stage**	**Upper (°C)**	**Lower (°C)**	**Refs.[1]**
Scaphirhynchus platorynchus	Shovelnose Sturgeon	Eggs	28	8	15	Eggs				Eggs	20	15	15
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile				Juvenile	22		16
		Adult				Adult				Adult	25	15	16
Notropis atherinoides	Emerald Shiner	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile				Juvenile	32-35.2		13	Juvenile	25	13	13
		Adult	34.5-35		13	Adult	28.9-30.7		13	Adult	23	15	13
Ictiobus bubalus	Smallmouth Buffalo	Eggs				Eggs				Eggs			
		Larvae				Larvae				Larvae			
		Juvenile	31.3		13	Juvenile				Juvenile			
		Adult				Adult				Adult	34	31	13
Polyodon spathula	American Paddlefish	Eggs				Eggs				Eggs			
		Larvae	28		17	Larvae	24		17	Larvae	20		17
		Juvenile	33.4-35.2		13	Juvenile				Juvenile			
		Adult				Adult				Adult	29	24	18
INVERTEBRATE													
Strophitus undulatues	Creeper Mussel[2]	Eggs				Eggs				Eggs			
		Glochidia				Glochidia				Glochidia			
		Juvenile				Juvenile				Juvenile	28	26	8
		Adult	39-42.2		7	Adult				Adult			
Megalonaisa nervosa	Washboard mussel	Eggs				Eggs				Eggs			
		Glochidia	28.4-31.3		22	Glochidia	15.6-27.2		22	Glochidia			
		Juvenile	34.0-34.2		22	Juvenile	27.2-30.0		22	Juvenile			
		Adult				Adult				Adult			
Hexagenia spp.		Eggs				Eggs				Eggs	34	31	10

Species	Common Name	Life Stage	Acute			Life Stage	Chronic			Life Stage	Optimal Thermal Range		
			Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]		Upper (°C)	Lower (°C)	Refs.[1]
	Burrowing Mayfly	Nymph				Nymph	27.1	26.1	11	Nymph	20	15	24
		Adult				Adult				Adult			
PLANT													
Vallisneria americana	Wild Celery	NA				NA	38	13	20	NA	28		20
PLANKTONIC													
Microcystis aeruginosa	HAB-forming cyanobacteria	NA	37	15	12	NA				NA	30	25	12

[1] Numbers denote references found in Table 3-12.

[2] Optimal temperature tolerances are based on the following species: *Epioblasma brevidens*, *Epioblasma capsaeformis*, and *Lampsilis fasciola.*

Table 3-12. List of References for RIS (Table 3-10) and Thermal Tolerances (Table 3-11)

Reference Number	Citation
1	U.S. Army Corps of Engineers GLMRIS Team. 2012. Commercial Fisheries Baseline Economic Assessment - U.S. Waters of the Great Lakes, Upper Mississippi River, and Ohio River Basins.
2	HDR Engineering, Inc. 2009. Quad Cities Nuclear Station: Adjusted Thermal Standard CWA Section 316(a) Demonstration (Final Draft).
3	Pearson, W. D. and L.A. Krumholz. 1984. Distribution and status of Ohio River fishes (No. ORNL/Sub-79-7831/1). Louisville Univ., KY (USA). Water Resources Lab.
4	Havlik, M. E. and J. S. Sauer. 2000. Native freshwater mussels of the upper Mississippi River system. US Department of the Interior, USGS, Upper Midwest Environmental Sciences Center.
5	Hoopes, D. T. 1960. Utilization of mayflies and caddis flies by some Mississippi River fishes. Transactions of the American Fisheries Society, *89*(1), 32-34.
6	Manier, J. T. 2014. Spatial and Temporal Dynamics of Phytoplankton Assemblages in Selected Reaches of the Upper Mississippi River: Navigation Pools 8, 13, and 26. Doctoral dissertation, University of Wisconsin – LA Crosse.
7	Galbraith, H. S., C. J. Blakeslee, and W. A. Lellis. 2012. Recent thermal history influences thermal tolerance in freshwater mussel species (Bivalvia: Unionidae). Freshwater Science 31(1): 83-92.
8	Carey, C. S., J. W. Jones, E. M. Hallerman, and R. S. Butler. 2013. Determining optimum temperature for growth and survival of laboratory-propagated juvenile freshwater mussels. North American Journal of Aquaculture, 75(4), 532-542.
9	Winter, A., J. J. Ciborowski, and T. B. Reynoldson. 1996. Effects of chronic hypoxia and reduced temperature on survival and growth of burrowing mayflies, (Hexagenia limbata) (Ephemeroptera: Ephemeridae). Canadian Journal of Fisheries and Aquatic Sciences, 53(7), 1565-1571.
10	Tennessen, K. J. and J. L. Miller. 1978. Effects of thermal discharge on aquatic insects in the Tennessee Valley (No. PB-295415). Tennessee Valley Authority, Muscle Shoals, AL (USA). Div. of Environmental Planning.
11	Gaufin, A. R. 1973. Water quality requirements of aquatic insects. For sale by the Supt. of Docs., USGPO.
12	Konopka, A. and B. Holt. 1978. Effect of Temperature on Blue-Green Algae (Cyanobacteria) in Lake Mendota. Applied and Environmental Microbiology 36(4): 572-576.
13	Yoder, C. O., E. T. Rankin, and B. J. Armitage. 2006. Re-evaluation of the technical justification for existing Ohio River mainstem temperature criteria. Report to Ohio River Valley Water Sanitation Commission. Tech. Rept. MBI/05-05-2. Columbus, OH. 56 pp. + 4 appendices.

Reference Number	Citation
14	Wismer, D. A. and A. E. Christie. 1987. Temperature relationships of Great Lakes fishes. Spec. publ. /Great Lakes Fishery Commission.
15	Kappenman, K. M., M. A. H. Webb, and M. Greenwood. 2013. The effect of temperature on embryo survival and development in pallid sturgeon Scaphirhynchus albus (Forbes and Richardson 1905) and shovelnose sturgeon S. platorynchus (Rafinesque, 1820). Journal of Applied Ichthyology 29(6): 1193-1203.
16	Blevins, D. W., D. G. Elliott, A. P. Farrell, R. E. Wolf, S. A. Morman, P. L. Hageman and G. S. Plumlee. 2011. Water-quality requirements, tolerances, and preferences of pallid sturgeon (Scaphirhynchus albus) in the lower Missouri River. US Department of the Interior, USGS.
17	Kroll, K. J., J. P. Van Eenennaam, S. I. Doroshov, J. E. Hamilton, and T. R. Russell. 1992. Effect of water temperature and formulated diets on growth and survival of larval paddlefish. Transactions of the American Fisheries Society 121(4): 538-543.
18	Paukert, C. P. and W. L. Fisher. 2000. Abiotic factors affecting summer distribution and movement of male paddlefish, Polyodon spathula, in a prairie reservoir. The Southwestern Naturalist, 133-140.
19	Ross, S. T. and W. M. Brenneman. 2001. The inland fishes of Mississippi. Univ. Press of Mississippi.
20	Bartleson, R. D., M. J. Hunt, and P. H. Doering. 2014. Effects of temperature on growth of Vallisneria americana in a sub-tropical estuarine environment. Wetlands Ecology and Management 22(5): 571-583.
21	Missouri Department of Conservation. 2016. “Golden Redhorse”; located at: http://mdc.mo.gov/discover-nature/field-guide/golden-redhorse
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23	Borsuk, F. 2016. Personal communication- description of analysis conducted by Jeff Thomas (fisheries biologist) at ORSANCO on cyprinid species collected in Ohio River between 1990-2015.
24	L. L. Wright and J. S. Mattice. 1985. Emergence Patterns of Hexagenia bilineata: Integration of Laboratory and Field Data. Freshwater Invertebrate Biology 4:3, 109-124

3.6 Thermal Refugia

3.6.1 Introduction

Thermal regimes within rivers can be extremely heterogeneous over space and time (e.g., Fullerton et al., 2015). Understanding this complexity is important to developing indicators of the degree of protection afforded to fish in these waters. Stream temperature data collected at high spatial resolution are useful, but typically only represent a snapshot in time, whereas high temporal resolution data are typically collected at only a few discrete points. Various methods have been proposed to interpolate between high temporal resolution point data (e.g., Isaak et al., 2010, 2017) or to integrate high spatial resolution snapshots with high temporal resolution timeseries (e.g., Vatland et al., 2015). But because these methods are primarily statistically based, they typically do not fully account for the physical processes that drive stream temperature variability in natural systems. Sullivan et al. (2021) have proposed a typology to define and characterize thermal refuges, which can be used to reduce ambiguity in identifying thermal refuges, that could be a useful resource to facilitate consistency in future studies.

Some of the most persistent thermal refugia in natural river systems are those that occur at tributary junctions. Previous studies have documented both the persistence of these refugia under a wide range of flow conditions (e.g., Ebersole et al., 2015; Dugdale et al., 2015); and the heavy use of these refugia by migrating fish (e.g., High et al., 2006; Sutton et al., 2007; Ritter et al., 2020; Sullivan et al., 2021). Because of their persistence and heavy utilization, these cold water refugia at tributary junctions could be important priorities for conservation, particularly as ambient mainstem stream temperatures increase in a warming climate (e.g., Ebersole et al., 2015; Isaak et al., 2016; FitzGerald et al., 2021). An ability to develop simple models to predict the temperature, spatial extent, and temporal persistence of these refugia under a range of flow conditions would therefore be a valuable tool for regulatory agencies and water managers.

This section summarizes some of the relevant literature on cold water refugia at tributary junctions, with a focus on developing simple methods and tools to estimate the temporal and spatial extent of these refugia under a range of flow conditions. It then describes publicly available sources of data that can be used to establish general relationships among thermal refuge size, relative temperature of refugia and ambient mainstem stream temperature, and tributary and mainstem stream flow conditions. Finally, this section describes some data compilation and analysis steps that can be undertaken to develop a basic understanding of how thermal refugia might change under different flow and temperature conditions, relying on inexpensive, screening-level analyses of publicly available information. These methods can be used as a roadmap for understanding the general behavior of tributary junction thermal refugia in specific locations, and for developing targeted, site-specific studies where a deeper understanding is required.

The information contained here is intended only to provide a general approach on how one might characterize thermal refugia at tributary junctions. The analyses contained are not comprehensive, nor are these summaries intended to provide formal guidance on how to characterize cold water refugia at tributary junctions. The end of this section includes some examples and recommendations of how detailed, site-specific studies might be undertaken to achieve a more thorough understanding of thermal refugia at particular locations or times.

Summary of Relevant Literature

The importance of thermal refugia for migrating fish—particularly salmonids—has received a significant amount of attention in the literature (e.g., Sutton et al., 2007; Dugdale et al., 2013, 2015; Isaak et al., 2016). This section summarizes only a small number of these studies, focusing on those relevant to understanding and modeling the spatial variability in stream temperatures in general, and thermal refugia at tributary junctions in particular.

3.6.2 General Studies of Thermal Regimes in Rivers

Developing a complete physically-based model describing stream temperatures in natural systems is extremely computationally intensive. Furthermore, it requires a dense monitoring network of groundwater and surface water flow and temperature, which is rarely available (e.g., Loinaz et al., 2014; Wobus et al., 2015). As a result, the majority of studies characterizing thermal regimes of natural river systems have focused primarily on statistically-based rather than physically-based methods of characterizing stream temperatures throughout watersheds. In some cases, these models are purely statistically-based, and combine at-a-station thermal monitoring data with synoptic temperature measurements derived from remote sensing (e.g., Vatland et al., 2015).

In other cases, investigators have used dense networks of point monitoring data or thermal infrared (TIR) imagery and supplemented those data with simplified basin characteristics such as elevation, slope, or insolation to develop multivariate statistical models (e.g., Isaak et al., 2010; McNyset et al., 2015; O'Sullivan et al., 2019). Gallice et al. (2015) summarized nearly 40 different studies of statistical stream temperature modeling, the majority of which were published over the previous decade. Extending on that previous work, Gallice et al. (2015) proposed a hybrid physically- and statistically-based approach that solves a simplified energy balance model, using landscape features such as channel width, topographical shading, and air temperature to parameterize unknown terms.

Spatial stream network models are another predictive tool (Fuller et al., 2021; EPA, 2021). SSN models can predict thermal heterogeneity across space, including headwater streams, and can include tributary discharges to represent cold water inputs. EPA's Columbia River Cold Water Refuges Plan includes SSN temperature estimates for 191 tributaries into the Columbia River (EPA, 2021). These models are particularly useful if data for covariates are available at a temporal resolution similar to the water temperature data (Fuller et al., 2021). Incorporating TIR data into SSN models can help identify key model variables, while also identifying cold water inputs or refuges that are otherwise not captured by a statistical model (Fuller et al., 2021).

Although various studies have shown success modeling the temporal and spatial variability of stream temperatures over large spatial scales, it is also recognized that these basin-scale models cannot simulate the full thermal complexity of natural river systems. In particular, while stream temperatures increase monotonically downstream in some river systems, many rivers exhibit highly complex patterns of stream temperature that cannot be captured by simplified geostatistical models (e.g., Fullerton et al., 2015). Some of the landscape features identified as drivers of local complexities in stream temperature include groundwater inputs, variable shading from riparian vegetation, and cold water inputs from tributaries (Fullerton et al., 2015); see Sullivan et al. (2021) for a proposed typology based on changes in ecological function to characterize features that influence thermal refugia.

Dugdale et al. (2013) suggested that thermal refugia at tributary junctions are the most spatially and temporally persistent landscape features driving thermal complexity in natural systems. Furthermore, detailed studies of fish migration demonstrate that thermal refugia at tributary junctions are heavily utilized by migrating salmonids, including Coho salmon, Chinook salmon, and steelhead (e.g., High et al., 2006; Sutton et al., 2007). Consequently, a detailed understanding of how tributary junction thermal refugia behave under different conditions is warranted.

Other recent studies on thermal refugia include the Lower Willamette River Cold-Water Refuge Narrative Criterion Interpretation Study (Oregon DEQ, 2020) and the Lower Columbia River Thermal Refuge Study, 2015–2018 (Marcoe et al., 2018).

3.6.3 Detailed Studies of Thermal Refugia at Tributary Mouths

Recent work has demonstrated the importance of tributary thermal refugia for migrating salmonids (e.g., Sutton et al., 2007), and these refugia are likely to become ever more important as ambient stream temperatures increase in a warming climate (e.g., Isaak et al., 2016). An understanding of how these thermal refugia evolve under a range of conditions is therefore critical to regulators and water managers—both for projecting how temperature-sensitive fish might be affected by warming temperatures, and for prioritizing specific stream reaches for conservation (Steel et al., 2017).

A series of detailed studies of thermal refugia at tributary junctions has been conducted in the Pacific Northwest, with a particular focus on the Columbia River and its tributaries (e.g., Watershed Sciences LLC, 2003; Ebersole et al., 2015; McMillan et al., 2016; EPA, 2021) and the Klamath River (Sutton et al., 2007; Deas et al., 2006). These studies have included detailed thermal imagery to document the spatial extent of thermal refugia at snapshots in time, as well as dense networks of stream temperature monitors to document how these thermal refugia evolve in space and time.

Deas et al. (2006) deployed networks containing between 75 and 100 temperature sensors at the mouths of Beaver Creek and Red Cap Creek in the Klamath River basin of northern California. Deas et al. used this sensor network to monitor temperatures at high temporal resolution over a range of flow conditions, and to characterize how thermal refugia at these tributary mouths responded to different flow regimes. They found that the size and shape of the tributary junction thermal refugia varied throughout the day, and also varied as a function of the flow in the main stem of the Klamath River. In particular, they found that at both tributary mouths, the cold water refugia became smaller and narrower as mainstem flows increased due to regulation at an upstream dam site.

Although Deas et al. (2006) clearly demonstrate that the size and shape of thermal refugia at tributary mouths vary with flow condition; few studies have used the sensor networks necessary to develop generalizable rules for estimating the size and shape of thermal refugia at tributary mouths. One notable exception is Knudson (2012) who used detailed measurements from a tributary junction in British Columbia to calibrate a simplified, physically-based model of thermal mixing at the mouth of the Ryan River. The framework described by Knudson (2012) is described in more detail in Section 3.6.7.

EPA also recently published a detailed study on thermal refugia, the Columbia Cold Water Refuges Plan (EPA, 2021). This plan studied the lower Columbia River, which forms the border between Washington and Oregon and is an important reach for salmon spawning. The plan describes the extent of cold water refuges in the area, how the refuges are used by migrating fish, and steps to protect and further study these areas.

3.6.4 Data Sources and Analysis

Several publicly available datasets provide general information relevant to understanding thermal conditions at tributary junctions. This section summarizes those data sources and notes how the data can be used to develop a general understanding of tributary junction thermal refugia under a range of flow conditions. It then summarizes existing analytical methods and models that can be used in conjunction with these data to develop a more thorough understanding of how thermal refugia might evolve under a broader range of flow conditions.

3.6.5 Public Data Sources and Exploratory Data Analysis

Two of the primary controls on the size and shape of thermal refugia at tributary junctions are the flow and temperature in the tributary and the mainstem (Deas et al., 2006; Knudson, 2012). At a minimum, a physically-based model to estimate the size of a tributary thermal refuge therefore requires information on these two parameters. In many cases, flow and temperature information can be accessed from publicly available sources. Stream flow data at USGS gaging sites are widely available through the USGS National Water Information System (NWIS) http://waterdata.usgs.gov/nwis/rt and temperature data are available through the WaterWatch system: http://waterwatch.usgs.gov/wqwatch/. Both of these datasets are available through a real-time, Google Earth-based interface, where all of the data from each stream gage can be accessed at http://waterwatch.usgs.gov/?m=real&w=kml.

In addition to these data available from discrete points, spatially continuous stream temperature data can be accessed through the NorWeST database, which covers the entire western United States (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html).[17] This dataset was compiled through a consortium of state and regional agencies, using SSN modeling to interpolate between temperature measurements collected from >20,000 unique measurement sites (Isaak et al., 2017). Because of their spatial continuity, these data can be used to evaluate patterns of stream temperatures at much larger spatial scales, or they can be used to help identify locations where more detailed data collection is required. In some areas, the data on which the NorWeST model is based are at a sufficiently high spatial resolution that they can be used directly. In most cases, however, the temperature data contained in this database will be a model fit to relatively sparse measurement points and may not provide the temporal or spatial resolution required to assess detailed thermal structure at tributary junctions.

Streamflow and temperature data, where available, can be used to develop a general understanding of the flow conditions under which tributary junction thermal refugia are likely to be important. Using these data, an exploratory data analysis can aid in understanding how thermal refugia at tributary junctions evolve through the year, and when these refugia overlap with important periods of fish migration. In particular, there may only be certain times during the year when mainstem stream temperatures are high enough to be a concern for migrating fish, and when tributary temperatures are cool enough to moderate these high mainstem stream temperatures sufficiently to provide refugia for

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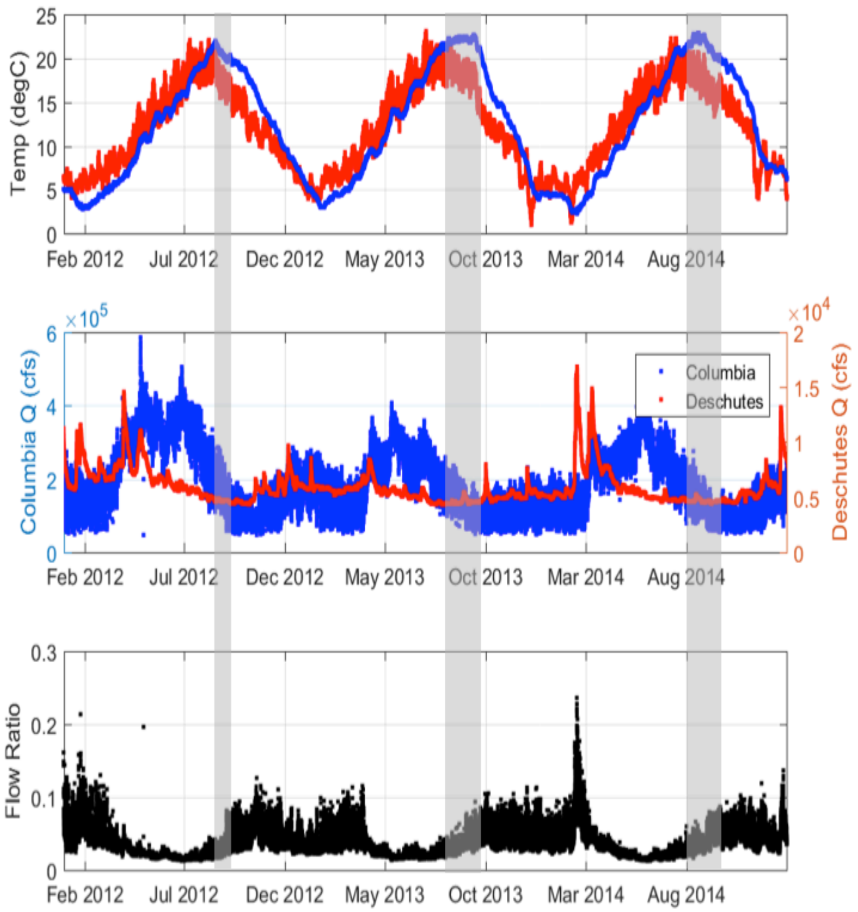
[17] NorEaST is a database of stream temperature data for New England, Mid-Atlantic, and Great Lakes regions. The NorEaST tool is not as extensive as NorWeST and does not include the predictive SSN component.

thermally-sensitive species. Characterizing these conditions would be useful prior to engaging in detailed analyses of tributary refugia (Deas et al., 2006; EPA 2021).

As an example of mainstem and tributary flow and temperature analysis, Figure 3-1 summarizes three years of tributary and mainstem stream temperature and flow data downloaded from NWIS for the mouth of the Deschutes River where it empties into the Columbia River (USGS, 2017). In this example, temperatures at the mouth of the Deschutes River peak in late July (Figure 3-1 upper panel, red line), whereas temperatures in the Columbia River peak in mid to late August (blue line). As a result, tributary inflows from the Deschutes only provide potential refuge from peak Columbia River temperatures (> 20°C) for a narrow window of time in the late summer. As shown in the lower plot, this late summer period also corresponds to the time of year when the ratio of flow in the Deschutes and Columbia is increasing. This change in flow ratio suggests that the thermal refuge is likely to increase in size during the late summer and early fall when Columbia River temperatures are highest.

In some cases, TIR imagery might be available to characterize the size of thermal refugia under a certain set of flow conditions (Watershed Sciences, 2003; Fullerton et al., 2015; McMillan et al., 2016; Mejia et al., 2020). When available, this imagery can be used to directly estimate the size of the thermal refuge at discrete snapshots in time. Due to the cost and specialized nature of thermal imagery, these images are unlikely to be available at multiple times for a waterbody; however, they are becoming more widely available with the use of unoccupied aircraft vehicles (UAVs) or drones (e.g., KarisAllen and Kurylyk, 2021; Kuhn et al., 2021), which have reduced costs and logistical challenges.



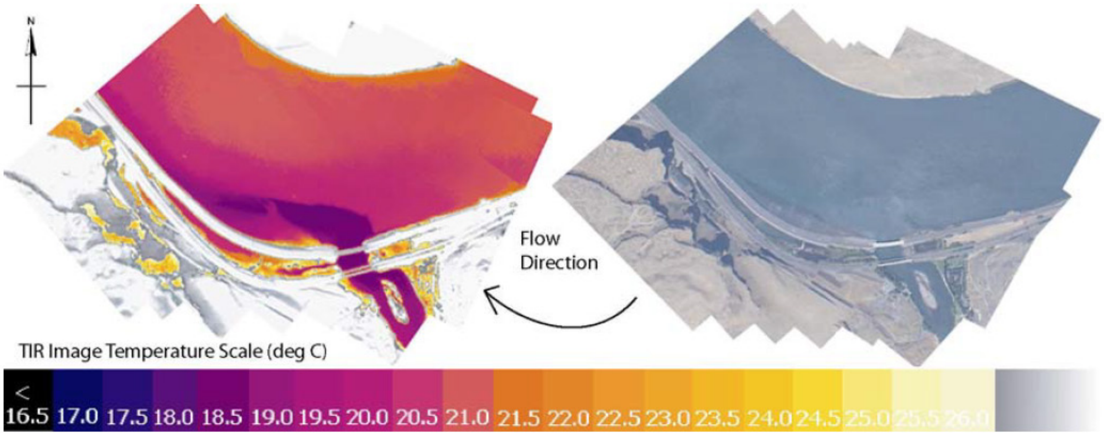
(Source: Based on USGS, 2017)

For illustrative purposes, grey bands highlight times of year when the Deschutes River temperature is lower than the Columbia AND the Columbia mainstem temperature is >20ºC.

Figure 3-1. Temperature (top panel) and flow (middle panel) for the Deschutes River at its mouth (red) and the Columbia River near The Dalles, Oregon (blue), approximately 19 kilometers (km) downstream, and the ratio of Deschutes flow to Columbia river flow (bottom panel).

However, the utility of thermal imagery could be expanded by comparing TIR images with visible or red-green-blue-band (RGB) imagery at the time of TIR image acquisition (Figure 3-2). In particular, RGB imagery has recently been used to incorporate physical habitat assessment in the identification and characterization of cold water refugia for different types of reach morphology (Kuhn et al., 2021). If thermal mixing zones can be clearly delineated in visible imagery based on this comparison (e.g., due to differences in turbidity, chlorophyll, etc. between the tributary and mainstem), the more widely available visible photographs might then be leveraged to characterize the size and shape of mixing zones under a broader range of flow conditions. Aerial imagery is available through online portals from the USGS (http://www.usgs.gov/pubprod/aerial.html) as well as through the “historical imagery” tool in Google Earth (https://www.google.com/earth/).

Visible aerial imagery is typically collected more frequently than TIR and may provide additional information on mixing zones downstream of tributary inflows. For example, Figure 3-3 shows two images from Google Earth, showing the junction of the Deschutes and Columbia Rivers at two different flow conditions. Based on these images, the mixing zone between the Deschutes and Columbia Rivers appears to penetrate further into the Columbia River in September 2009 than in November 2011.



(Source: Watershed Sciences LLC, 2003)

Cooler water from the Deschutes River can clearly be seen as darker purple in the left image, and corresponds broadly to a zone of higher turbidity water in the visible image.

Figure 3-2. Thermal IR image (left) and visible image (right) at the Deschutes-Columbia confluence.

Source: Google Earth.

Note that the mixing zone penetrates further into the Columbia in the September 2009 imagery relative to November 2011 imagery, consistent with the higher Deschutes to Columbia flow ratio during September 2009

Figure 3-3. Comparison of visible imagery at the Deschutes-Columbia confluence from September 10, 2009 (left) and November 3, 2011 (right).

This is consistent with data from USGS gaging records showing that the ratio of Deschutes to Columbia flow was also 25% larger in September 2009 than in November 2011 (0.05 vs 0.04). As described in more detail below, a broader range of imagery and flow conditions such as this could potentially be used to qualitatively inform relationships between flow conditions and thermal refuge size (e.g., Knudson, 2012).

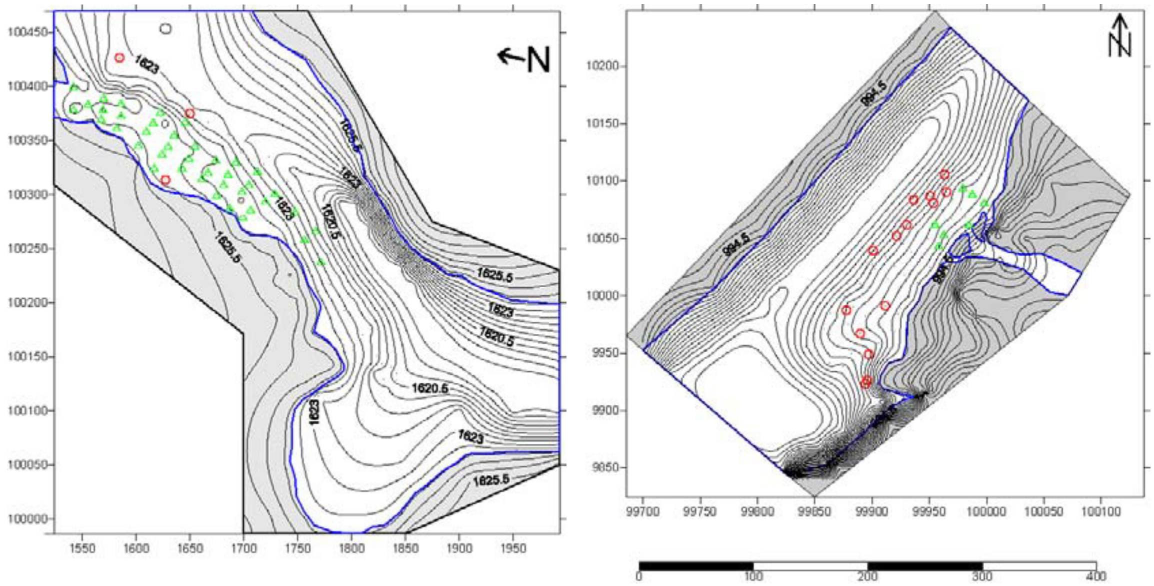
3.6.6 Field Data Collection

In most cases, remotely sensed data will not be available at a sufficiently high temporal resolution to characterize the evolution of thermal refugia at tributary mouths under a full range of flow conditions. This gap can be filled by deploying temperature loggers to monitor temperatures in the field. The most common temperature loggers include iBCod (https://thermodata.us/products/ibcod-loggers) or TidBit loggers (http://www.onsetcomp.com/products/data-loggers/utbi-001). Both of these sensors are fully contained, autonomous loggers capable of logging >2000 discrete temperature measurements at user-specified time intervals. Each logger is also approximately the size of a quarter, facilitating deployment at high spatial resolution which permits the monitoring of vertical temperature variation within a relatively shallow water column.

Deas et al. (2006) deployed between 75-100 iBCod loggers at the mouths of Beaver Creek and Red Cap Creek in the Klamath River basin, and logged temperatures at 30-minute intervals over the course of approximately one month in both settings. Figure 3-4 shows the monitoring networks that were established at each of these tributary junctions, and also illustrates which sites within the thermal refuge zone had temperatures statistically distinguishable from ambient temperatures in the mainstem. Using these data, Deas et al (2006) demonstrated that the size of the thermal refuge at Beaver Creek remained largely constant with increasing flow in the Klamath River, up to a threshold mainstem flow of ~1100 cubic feet per second (cfs). Above this mainstem flow, the thermal refuge became noticeably smaller and narrower. In this case, this threshold behavior was related to the presence of a gravel bar at the tributary junction, which had to be flooded to a significant depth before the tributary and mainstem stream flows became well-mixed. Local geomorphology is likely to also play a role in mixing dynamics at other tributary junctions.

Knudson (2012) deployed a network of TidBit temperature loggers in British Columbia to monitor thermal mixing at the confluence of the Lillooet River (mainstem) and the Ryan River (tributary). This system is much larger than the Klamath River, and temperature loggers were deployed at a coarser resolution than those in Deas et al. (2006). Based on Knudson's (2012) study, approximately half of the lateral mixing between the tributary and mainstem streams occurred within the first 1 km of the tributary junction. Downstream of this distance, mixing slowed until full mixing was achieved at a distance of approximately 4 km. As described below, Knudson (2012) used these monitoring data to calibrate a simple model of mixing dynamics as a function of tributary and mainstem flows.

EPA (2021) also collected data at tributary mouths as part of its Columbia River Cold Water Refuges Plan. Specifically, EPA mapped the temperature profile of the Columbia River and the tributaries, as well as information on the extent that salmonids traversed the cold water refuge.



Beaver Creek Confluence
(Mainstem Flow ~ 710 cfs)

Red Cap Creek Confluence
(Mainstem Flow ~ 1400 cfs)

<u>Source</u>: Modified from Deas et al. (2006).

<u>Left panel:</u> Beaver Creek confluence in upper left; mainstem flow from top left to bottom right, and Red Cap Creek. <u>Right panel:</u> Red Cap Creek confluence at middle right, mainstem flow from top right to bottom left, both in the Klamath River. Green triangles are loggers whose temperatures were statistically indistinguishable from the tributary temperature, and red circles are loggers whose temperatures were statistically indistinguishable from the mainstem temperature, at the flow conditions specified. Scalebars and contours in both images are in feet.

Figure 3-4. Temperature loggers deployed at the mouth of Beaver Creek.

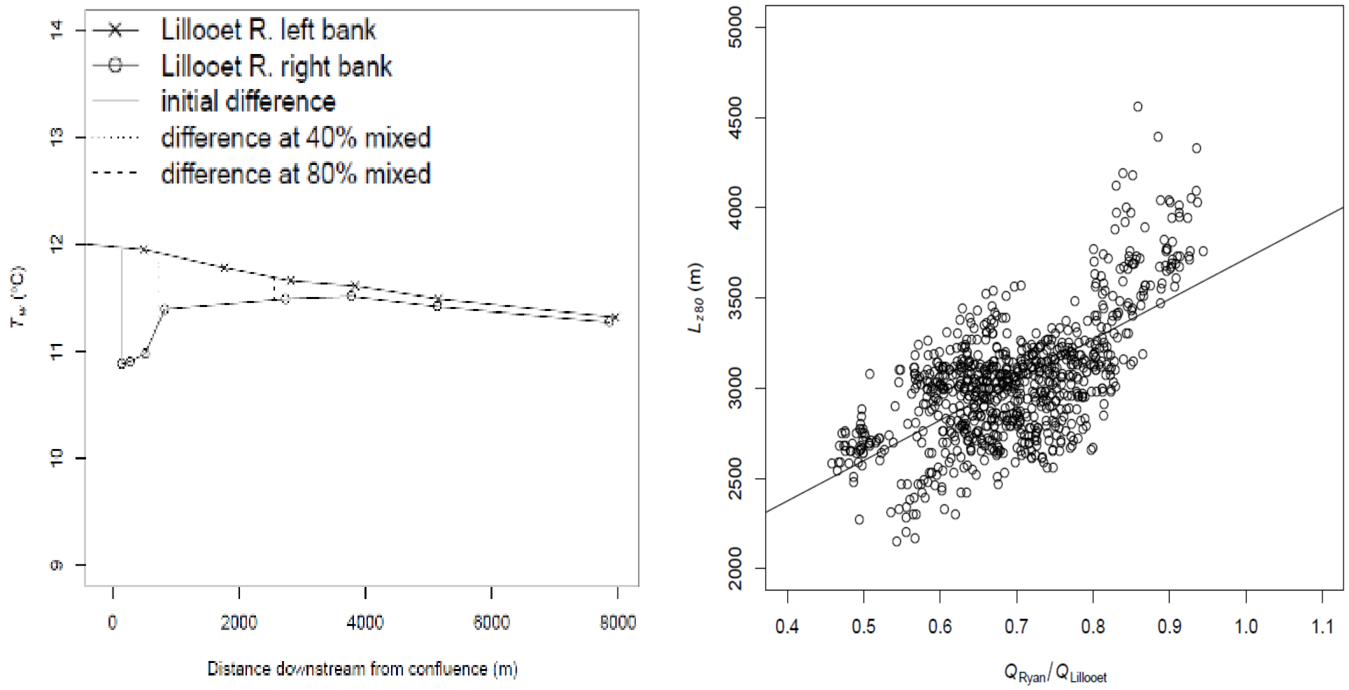
3.6.7 Modeling Thermal Plumes

Physically-based models of thermal refugia at tributary mouths can take the form of generalized scaling relationships, simplified one-dimensional (1-D) models, or full two-dimensional (2-D) or three-dimensional (3-D) models describing how thermal refugia are expected to evolve under different flow conditions. The type of modeling undertaken will depend on available resources and the amount of data available for the site of interest. General scaling relationships may be more appropriate in situations that are more data or resource constrained, whereas complete numerical models may be feasible only for projects with more comprehensive data and sufficient resources. Below are several examples, drawing on previous work where appropriate.

Simplified Scaling Relationships

As summarized above, the size and shape of a thermal refuge at a tributary mouth will typically depend on the relative flows in the tributary and mainstem stream (e.g., Deas et al., 2006). At the spatial scale of interest for most tributary thermal refugia, solar heating will be slow relative to physical mixing between tributary and mainstem stream waterbodies. Assuming there are not significant thermal impacts from groundwater inflows or other sources (e.g., Ebersole et al., 2015) temperature can therefore be treated as a conservative tracer, and the physical processes driving thermal mixing at tributary junctions are exactly analogous to the processes driving mixing for suspended sediment, contaminants, or other tracers. There is a rich literature describing these mixing processes (e.g., Rutherford, 1994). Knudson (2012) used this literature to calibrate a generalized model summarizing the evolution of a tributary thermal plume due to transverse mixing.

Knudson (2012) measured temperatures at opposite banks of the Lillooet River at specified intervals downstream of the confluence with the Ryan River. Since the thermal plume from the Ryan River remained along the right bank of the Lillooet River, Knudson (2012) used the temperature difference across the river as a proxy for the degree of transverse mixing (Figure 3-5).



Source: *Knudson, 2012*

Left: The difference in water temperatures between the left and right banks was used as a proxy for the completeness of mixing. Right: Downstream distance to 80% mixing is broadly positively correlated with the ratio of tributary to mainstem stream flow ($Q_{Ryan}/Q_{Lillooet}$). Thus, the tributary thermal impact is larger for higher tributary inflows.

Figure 3-5. Example of thermal measurements in the Lillooet River downstream of the confluence with the Ryan River.

Knudson (2012) found that the most rapid mixing occurred close to the confluence, possibly because the tributary inflow helped push cooler tributary water out into the mainstem stream and increased turbulence near the confluence. Consistent with this hypothesis, Knudson (2012) also found that the transverse mixing coefficient was positively correlated with the ratio of tributary to mainstem stream flow. Thus, mixing is more efficient when tributary inflows are high relative to the mainstem stream, and less efficient when tributary inflows are lower. This is consistent with Deas et al. (2006) who found that tributary thermal plumes at the Beaver Creek and Red Cap Creek confluences were smaller for higher mainstem stream flows.

The Lillooet system has important differences from systems such as the Columbia or the Klamath, including river width, depth and the type of bed. However, the general approach outlined by Knudson (2012) could be extended to other settings where comprehensive datasets are available to establish simplified scaling relationships among tributary and mainstem stream flows, transverse mixing, and thermal refuge size.

Numerical Models

In cases where adequate data are available, it may be possible to develop a full numerical model to simulate thermal conditions at the tributary junction of interest. Numerical models typically solve systems of equations describing conservation of mass, momentum and/or energy, and can be used to simulate a range of conditions similar to, or slightly broader than, the conditions to which they are calibrated. Because these numerical models solve fundamental physical equations, they should be equally useful regardless of whether they are used to describe the evolution of warm water inputs to mainstem streams (e.g., from power plant effluents) or cold water inputs at tributary junctions. Thus, the relative benefits and drawbacks of the models, previously described in Section 3.1, would also apply to modeling of thermal refugia at tributary junctions.

2-D and 3-D Numerical Models

Deas et al. (2006) reviewed the potential utility of 11 numerical models for simulating thermal refugia, focusing on parameters such as cost, number of dimensions (2-D vs 3-D), and applicability to the Klamath River system.[18] As a proof-of-concept, Deas et al. (2006) chose the Unstructured Grid Tidal, Residual, Inter-Tidal Mudflat (UnTRIM) model to simulate thermal conditions at Beaver Creek. Deas et al. (2006) summarize some of the input parameters required to run the UnTRIM model, including:

- Bathymetry
- Bed roughness
- Bed slope
- Boundary conditions for water elevation and temperatures
- Initial conditions for water elevation and temperature throughout the domain, from which initial flow rates can be calculated

A similar set of parameters would be necessary to apply any model (e.g., EFDC) suitable for this application.

Based on qualitative comparisons between measured and modeled temperatures at the Beaver Creek confluence, Deas et al. (2006) indicated that the UnTRIM model was largely successful at simulating temperatures recorded by their iBCods for one set of flow conditions (Figure 3-6). However, these results were not extended to other flow conditions in this screening-level analysis. Because the Deas et al. (2006) study was largely a screening-level analysis, they focused model calibration on a narrow range of flow regimes. In addition, Deas et al. (2006) evaluated the success of their model based on a qualitative assessment of its ability to represent temperatures and a very limited set of velocity measurements at specified points in their model domain. In field settings where thermal refugia can be

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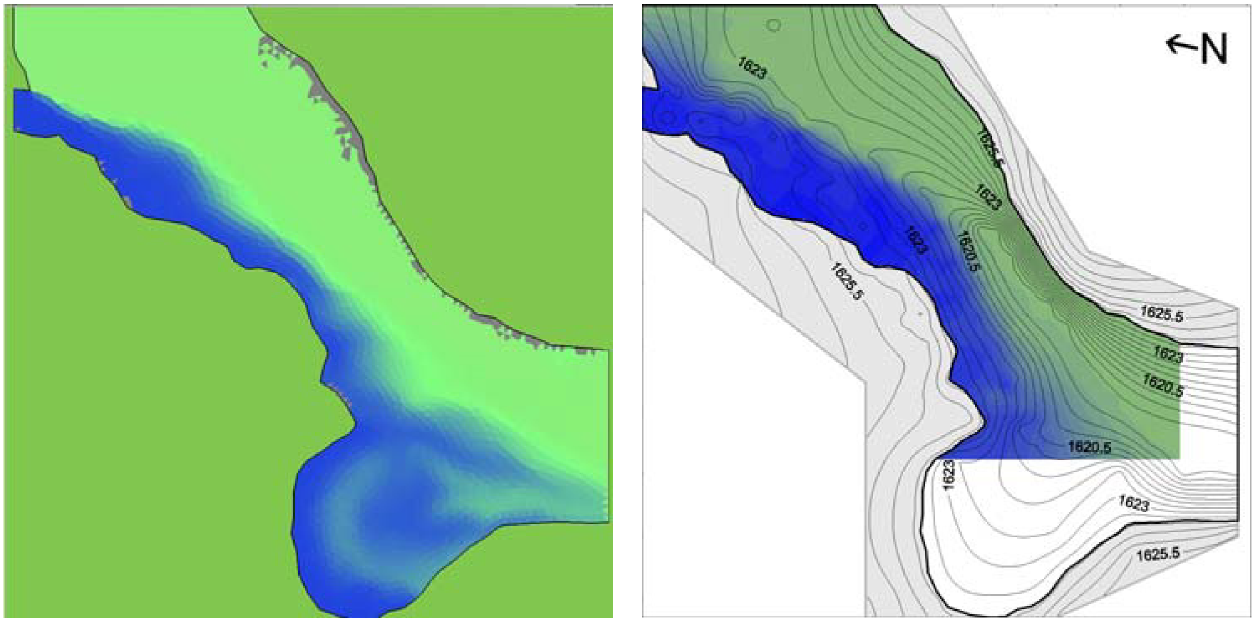
[18] Of the models considered, several overlapped with models reviewed in Section 4.1: CORMIX, CE-QUAL-W2, EFDC, and MIKE3.

monitored over a broader range of flows, it would be preferable to calibrate numerical models to a broader set of measurements including velocity and/or water surface elevations.



UnTRIM model

iBCod Data

<u>Source:</u> Modified from Deas et al. (2006)

Shades of blue represent relative water temperatures for modeled and measured flows. Mainstem flow from upper left to lower right; Beaver Creek confluence at upper left.

Figure 3-6. Comparison of UnTRIM modeled temperatures (left) to measured temperatures (right) at the Beaver Creek confluence with the Klamath River.

Simplified Numerical Models

Simplified numerical models can be used to estimate the volume and temperature of cold water plumes for tributaries with simple hydrologic connections to a mainstem river. These analyses can be particularly useful to evaluate a stream network with many tributaries. As part of the Cold Water Refuges Plan for the Columbia River, EPA conducted CORMIX modeling of tributary plumes to the Lower Columbia (Cope et al., 2017). Average August conditions were simulated at 26 tributaries to estimate plume width, depth, volume, and temperature. Input data included tributary temperatures, flow, depth, width, velocity, and characteristics of the tributary mouth relative to the Columbia River as well as temperature, flow, depth, and velocity of the river itself. Results in refugia volumes varied by several orders of magnitude, depending on temperature differences and tributary flow.

EPA conducted sensitivity analyses to quantify the uncertainty range of the predictions since model inputs had large variability. These analyses suggested that the predictions for volume were appropriate as order-of-magnitude estimates. Despite the uncertainty, the CORMIX results were determined useful to identify significant cold water refugia plumes (Cope et al., 2017).

The study also compared the CORMIX estimated volumes to the differential temperature flux (temperature difference times tributary flow) and found a strong correlation. This relationship was then applied to other un-modeled tributaries to estimate plume volumes based on their tributary flow and temperature difference. The regression analyses determined that where tributary temperature differences from the mainstem were small (less than 3°C), CORMIX under-predicted refugia volume; therefore, a regression-based estimate was used for these tributaries instead of the CORMIX results (Cope et al., 2017).

3.6.8 Approach to Characterize Thermal Refugia

The sections above summarize some of the data and analytical methods used in previous studies to understand the evolution of thermal refugia at tributary junctions. This information is synthesized below along with an outline of a more detailed approach that could be taken to characterize thermal refugia at tributary mouths. Although the Columbia River is used below as an example (EPA, 2021), this type of approach could be applied to other river systems where the presence of thermally sensitive fish requires an understanding of thermal conditions over time and space. Steel et al. (2017) summarized how recent advances in data availability, modeling, and biological implications can inform future research on and management of thermal regimes, suggesting that researching and compiling the most recent information is important to evaluate thermal refugia.

Proposed Approach

A proposed approach to characterize thermal refugia at tributary mouths includes the following steps, which can be scaled depending on study objective:

- **Collect publicly available data**. To characterize the availability of thermal refugia, available flow and temperature data from tributary and mainstem gaging stations of interest could be compiled. These include daily or sub-daily temperature and flow measurements, where available, as described in Section 3.6.5, and drawing on existing databases such as the ones compiled through the NorWeST project (e.g., Isaak et al., 2010). In addition to federal sources, data may be available from states, local utilities, and nonprofits. An exploratory data analysis can then be conducted (e.g., Figure 3-2) to determine which of the tributary junctions have the most complete thermal and discharge data and when tributary inflows are most likely to create thermal refugia in the mainstem. Note that temperature and flow gaging stations tend to be located on larger streams and rivers, thus screening for smaller tributaries that are excluded from flow and temperature monitoring networks may require targeted field visits (see the next step).
- **Collect targeted field data**. Based on the analysis above, a subset of these tributary junctions can be targeted for a more comprehensive study to better understand the localized conditions that determine the size and temperature of tributary junction thermal refugia. As summarized in Section 3.6.6, supplementary data collection could include available imagery to evaluate the spatial extent of this refuge at representative flow conditions. This spatial extent, along with information on timing of cold water inputs determined from the exploratory data analysis, can be used to develop a field sampling strategy targeted to specific windows of time and/or locations. Focusing field sampling efforts on a narrow window of time allows the collection of high temporal resolution temperature data to characterize sub-daily variability in tributary, mainstem, and mixing zone temperatures. Following Deas et al. (2006) these data can then be analyzed to estimate the spatial extent of the thermal refuge for different tributary and mainstem flow and temperature conditions.

- **Collect thermal imaging data**. As funds allow, collection of thermal imaging data for discrete snapshots in time could be useful, both to validate the field-based temperature data collection and to determine whether additional field sampling locations are required to fully delineate the thermal refuge. Thermal imagery would be collected early in the season to allow a mid-course correction of the field sampling locations, if needed.
- **Develop thermal models**. The information collected above can also be used to configure and calibrate thermal models to better understand the spatial extent and ambient temperature of thermal refugia at the locations of interest. Depending on the quality of available input data and the desired resolution of outputs, these models could take the form of simplified models and scaling relationships describing the size of thermal refugia under different flow conditions, or more complex numerical mixing models (see Section 3.6.7).
- **Targeted fish sampling.** Previous work has demonstrated that sensors can be placed on migrating salmonids to track fish migration patterns, how they use thermal refugia, and their integrated thermal dose (e.g., Sutton et al., 2007; Keefer et al., 2015; Ritter et al., 2020). This information could then be used in conjunction with ongoing and past studies to better understand and quantify the importance of tributary junction thermal refugia.

Example of Approach: Application to the Columbia/Deschutes Confluence

As an example of the feasibility of applying these methods to evaluate the spatial and temporal extent of refugia, the availability and use of data for the Deschutes and Columbia River confluence are assessed in several studies described below.

An evaluation of available USGS NWIS data demonstrated that a good temporal record of flow and temperature data were available for the Deschutes. Data for the Columbia mainstem were also available, although the gaging station is located farther downstream than might be desirable. Based on an exploratory data analysis (e.g., Figure 3-2), it is clear that thermal refugia at this tributary junction are most important in the late summer, when the temperature of the Deschutes is cooler than the Columbia River, and the mainstem water temperatures are sufficiently high that salmonids might seek refuge in this cooler water. August mean temperature estimates for 1993-2011 in the Deschutes River are also available from SSN modeling (EPA, 2021).

As summarized above, there are limited thermal imaging data available showing the extent of the thermal refuge at the Deschutes River confluence. At present, TIR images are available for 2 snapshots in time: August 2, 2002 (Watershed Sciences, 2003) and July 26, 2014 (McMillan et al., 2016). The 2002 imagery is incomplete and does not illustrate the full extent of the thermal plume on this date. Furthermore, USGS flow data are not available for the Columbia or Deschutes rivers for 2002; thus, it is not currently possible to use these TIR data to evaluate how the size and shape of the thermal refuge varies with flow conditions.

However, as illustrated in Figure 3-4, there is some qualitative evidence from visual aerial imagery that the Deschutes tributary plume size and shape varies with flow conditions. In particular, based on just two images in which the tributary plume can be delineated, the apparent mixing zone between the Deschutes and Columbia Rivers appears to penetrate further into the Columbia River as the Deschutes to Columbia flow ratio increases. If possible, it would be useful to locate a wider array of thermal and/or visible imagery from a broader range of tributary and mainstem stream flow conditions to provide a means of developing a more quantitative relationship between refuge size and flow ratio over a full range of summer flow conditions.

Additional spatially detailed temperature data sets for the Deschutes/Columbia confluence are not available. Thus, collection of more detailed temperature data, as described above, would be helpful to characterize the mixing zone over a range for flow and temperature conditions. The visual and TIR imagery could be used to inform the deployment of the temperature sensors.

In addition, a simplified mixing model could be developed using the basic tributary and mainstem flow and temperature data from the USGS gaging stations to estimate the spatial and temporal extent of the mixing zone. While this approach is useful for other tributaries, EPA conducted a CORMIX model and determined that a regression equation was more accurate in estimating refugia volume for tributaries where the temperature differential (ΔT) was less than 3°C. Therefore, as an alternative, EPA estimated the volume of the Deschutes River plume using the regression approached described in Section 3.6.7 (Cope et al., 2017).

Based on the current understanding of the Deschutes River, EPA has identified several actions to protect and enhance the cold water refuge (EPA, 2021). If in the future it is determined that additional study is needed and depending on the degree of spatial detail desired, it may be useful to develop a comprehensive 2-D or 3-D thermal model of this tributary refuge. If so, in addition to flow and temperature, it would also be necessary to obtain detailed information on the bathymetry and roughness of the Columbia River. This is because a full 2-D or 3-D model requires these inputs to solve the full system of equations describing flow and mixing in the mainstem Columbia River. Other parameters necessary to develop and calibrate such a model would depend on the code chosen, as described in Section 3.1. To be of greatest use, this model would also need to be calibrated to field data from as wide a range of flow and temperature conditions as possible. Finally, if possible, it would be most useful to combine the field and modeling studies with contemporaneous fish tagging studies, to provide data to understand how salmonids use these thermal refuges, which is currently estimated as the lower 3.2 miles of the river (EPA, 2021).

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Steel, E. A., Beechie, T. J., Torgersen, C. E., and A. H. Fullerton. 2017. Envisioning, quantifying, and managing thermal regimes on river networks. BioScience, 67(6), 506–522.

Sullivan, C. J., Vokoun, J. C., Helton, A. M., Briggs, M. A., and B. L. Kurylyk. 2021. An ecohydrological typology for thermal refuges in streams and rivers. Ecohydrology, 14, e2295.

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Watershed Sciences, LLC, 2003. Aerial Surveys in the Fifteenmile Creek Basin. Thermal Infrared and Color Videography. Final Report. Revised March 31, 2003.

Wobus, C., Prucha, R., Albert, D., Woll, C., Loinaz, M., Jones, R., and C. Travers. 2015. Hydrologic Alterations from Climate Change Inform Assessment of Ecological Risk to Pacific Salmon in Bristol Bay, Alaska. PloS one, 10(12), e0143905.

3.7 Appendix A to Section 3: Fishery Species Inventories and Information

Below are links to inventories of fish species for each state in the specified region. These links provide a list of species present in the state and typically include information on the species, where it can be found, its biology, and other details.

3.7.1 Pacific Northwest Region

Alaska
Alaska Department of Fish and Game. 2016. “Fish Species Found in Alaska” (http://www.adfg.alaska.gov/index.cfm?adfg=animals.listfish)

California
University of California at Davis, Division of Agriculture and Natural Resources. 2016. “California Fish Website” (http://calfish.ucdavis.edu/species/)

Idaho
American Fisheries Society; Idaho Chapter. 2016. “Fishes of Idaho” (http://www.idahoafs.org/fishes.php)

Montana
Montana Fish, Wildlife, and Parks. (Undated). “Fish Identification” (https://fwp.mt.gov/fish/species)

Oregon
Oregon Department of Fish and Wildlife. 2014. “Fish” (http://www.dfw.state.or.us/fish/crp/freshwater.asp)

Washington
University of Puget Sound – Slater Museum of Natural History. 2016. “Freshwater Fishes of Washington” (https://www2.pugetsound.edu/academics/academic-resources/slater-museum/biodiversity-resources/fishes/freshwater-fishes-of-washingto/)

Columbia River
NOAA, USFWS and U.S. Geological Survey (USGS). Undated. “Species of Fish Collected in the Columbia River Estuary” (https://www.fws.gov/uploadedFiles/Region_1/NWRS/Zone_2/Willapa_Complex/Julia_Butler_Hansen/Documents/Species%20of%20Fish%20Collected%20in%20the%20Columbia%20River%20Estuary.pdf)

3.7.2 Great Lakes Region

Illinois
IL Fish Finder. 2020. “Fish Species List” (http://www.ilfishfinder.com/view_all_fish_types.php)

Indiana
Indiana Wildlife Federation. Undated. Fish. (https://indianawildlife.org/education/native-animals/fish/)

Michigan
Michigan Department of Natural Resources. 2021. “Learn about Michigan’s Species - Fish” (https:/www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614---,00.html)

Minnesota
Minnesota Department of Natural Resources. 2021. “Fishes of Minnesota” (http://www.dnr.state.mn.us/fish/index.html)

New York
New York Department of Environmental Conservation. 2021. “Freshwater Fishes of New York Series” and “Fish Atlas Maps of New York. (http://www.dec.ny.gov/animals/269.html)

Ohio
Ohio Department of Natural Resources. Undated. Discover and Learn - Fish (https:/ohiodnr.gov/wps/portal/gov/odnr/discover-and-learn/animals/fish)

Pennsylvania
Pennsylvania Fish and Boat Commission. 2021. “Pennsylvania Fishes” (https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/default.aspx)

Wisconsin
University of Wisconsin Sea Grant Institute. 2021. “Wisconsin Fish Identification” (https://www.seagrant.wisc.edu/fish-id/)

Additional: Central Michigan University. Zooplankton of the Great Lakes. (undated) (http://people.cst.cmich.edu/mcnau1as/zooplankton%20web/).

3.7.3 Middle Atlantic Region

Habitat Requirements for Chesapeake Bay Living Resources
http://www.chesapeakebay.net/documents/Habitat_Requirements_for_Chesapeake_BayLiving_Resources.pdf

Distribution of Fishes in Pennsylvania Rivers: Susquehanna River, Delaware River, Potomac River
https://www.fishandboat.com/Fish/PennsylvaniaFishes/Documents/speciesapp.pdf

Fishes of the Hudson River in New York
http://www.dec.ny.gov/docs/remediation_hudson_pdf/hrepfishlist.pdf

Fishes of the Delaware River (New Jersey list)
http://www.state.nj.us/dep/fgw/artdelstudy_factsheets.htm

Fishes of Virginia
http://www.dgif.virginia.gov/wildlife/fish/

Pennsylvania Fishes
https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/default.aspx

West Virginia Fish
https://dep.wv.gov/WWE/getinvolved/sos/Pages/Fishes.aspx

American Shad facts
http://www.asmfc.org/uploads/file/Chp2_5_Shad_RiverHerring.pdf

3.7.4 Inland Great Rivers Region

Arkansas
Arkansas Game and Fish Commission. 2021. “Fishing by Species” (https://www.agfc.com/en/fishing/sportfish/)

Illinois
Illinois Department of Natural Resources. 2021. “Fish Species in Illinois” (http://www.ifishillinois.org/species/species.html)

Indiana
Indiana Department of Natural Resources. 2021. “Fishes of Indiana List” (https://www.in.gov/dnr/fish-and-wildlife/nongame-and-endangered-wildlife/fish-and-freshwater-mussels/fishes-of-indiana-list/)

Iowa
Iowa Department of Natural Resources (IDNR). 2021. “Iowa Fish Species” (http://www.iowadnr.gov/Fishing/Iowa-Fish-Species)

Kentucky
Kentucky Department of Fish and Wildlife Resources. 2021. “Fish Identification” (http://fw.ky.gov/Fish/Pages/Fish-Identification.aspx)

Louisiana
Louisiana Department of Wildlife and Fisheries. 2021. “Species Field Guide” (https://www.wlf.louisiana.gov/species/category/freshwater)

Minnesota
Minnesota Department of Natural Resources. 2021. “Fishes of Minnesota” (http://www.dnr.state.mn.us/fish/index.html)

Mississippi
MS Fish Finder. 2021. “Fish Species List” (http://www.msfishfinder.com/view_all_fish_types.php)

Missouri
Missouri Department of Conservation. 2021. “Fishing Species A-Z” (https://mdc.mo.gov/fishing/species)

Ohio
Ohio Department of Natural Resources. 2021. “Fish” (https://ohiodnr.gov/wps/portal/gov/odnr/discover-and-learn/animals/fish)

Pennsylvania
Pennsylvania Fish and Boat Commission. 2021. “Pennsylvania Fishes” (https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/default.aspx)

Tennessee
TN Fish Finder. 2021. “Fish Species List” (http://www.tnfishfinder.com/view_all_fish_types.php)

West Virginia
West Virginia Department of Natural Resources.2021. “Sportfish” (https://wvdnr.gov/plants-animals/sportfish/)

Wisconsin

University of Wisconsin Sea Grant Institute. 2021. “Wisconsin Fish Identification” (http://www.seagrant.wisc.edu/home/Default.aspx?tabid=604)

3.8 Appendix B to Section 3: Additional Information on Candidate RIS Species

Below are links to additional information on many common species; this information may be useful in selecting an appropriate RIS.

3.8.1 Fish

Alewife (Alosa pseudoharengus)
http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=490
http://fishbase.org/summary/Alosa-pseudoharengus.html
http://www.chesapeakebay.net/fieldguide/critter/alewife

American Gizzard Shad (*Dorosoma cepedianum*)
http://www.fishbase.org/summary/Dorosoma-cepedianum.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Dorosoma+cepedianum

American Paddlefish (*Polyodon spathula*)
http://www.fishbase.org/summary/Polyodon-spathula.html
http://www.iucnredlist.org/details/17938/0

American Shad (Alosa sapidissima):
http://www.chesapeakebay.net/issues/issue/shad
http://fishbase.org/summary/1584

Atlantic Menhaden (Brevoortia tyrannus)
http://www.chesapeakebay.net/issues/issue/menhaden#inline
http://fishbase.org/summary/Brevoortia-tyrannus.html

Atlantic Sturgeon (Acipenser oxyrhynchus)
http://www.chesapeakebay.net/fieldguide/critter/atlantic_sturgeon
http://www.fishbase.se/summary/Acipenser-oxyrinchus.html

Bay Anchovy (Anchoa mitchilli)
http://www.chesapeakebay.net/fieldguide/critter/bay_anchovy
http://fishbase.org/summary/Anchoa-mitchilli.html

Black Crappie (Pomoxis nigromaculatus)
http://www.fishbase.se/summary/3388
http://explorer.natureserve.org/servlet/NatureServe?searchName=Pomoxis+nigromaculatus

Bloater (Coregonus hoyi)
http://www.iucnredlist.org/details/5366/0
http://fishbase.org/summary/Coregonus-hoyi.html

Bluntnose Minnow (Pimephales notatus)
http://www.fishbase.se/summary/Pimephales-notatus.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Pimephales+notatus+

Brook Trout (Salvelinus fontinalis)
http://www.nps.gov/shen/learn/nature/brook-trout.htm
http://fishbase.org/summary/SpeciesSummary.php?ID=246&AT=brook+trout

Brown Bullhead (Ameiurus nebulosus):
https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82672---,00.html
http://fishbase.org/summary/Ameiurus-nebulosus.html

Bull Trout (Salvelinus confluentus)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Salvelinus+confluentus
https://fishbase.mnhn.fr/summary/SpeciesSummary.php?ID=2690&AT=bull+trout

Burbot (Lota lota):
https://www.dnr.state.mn.us/minnaqua/speciesprofile/burbot.html
http://www.fishbase.org/summary/Lota-lota.html

Channel Catfish (Ictalurus punctatus):
http://www.fishbase.org/summary/Ictalurus-punctatus.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Ictalurus+punctatus

Chinook Salmon (Oncorhynchus tshawytscha)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Oncorhynchus+tshawytscha
https://fishbase.mnhn.fr/summary/SpeciesSummary.php?id=244&lang=english

Chiselmouth (Acrocheilus alutaceus):
https://www.fishbase.de/summary/2741
http://explorer.natureserve.org/servlet/NatureServe?searchName=Acrocheilus%20alutaceus

Coho Salmon (Oncorhynchus kisutch)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Oncorhynchus+kisutch
https://fishbase.mnhn.fr/summary/245

Common Carp (Cyprinus carpio)
http://www.chesapeakebay.net/fieldguide/critter/common_carp
http://explorer.natureserve.org/servlet/NatureServe?searchName=Cyprinus+carpio

Common Shiner (Luxilus cornutus)
https://www.fishandboat.com/Fish/PennsylvaniaFishes/GalleryPennsylvaniaFishes/Pages/CarpsandMinnows.aspx
http://fishbase.org/summary/Luxilus-cornutus.html

Cutthroat Trout (Oncorhynchus clarki)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Oncorhynchus+clarki
https://fishbase.mnhn.fr/summary/2688

Fantail Darter (Etheostoma flabellare)
http://www2.dnr.cornell.edu/cek7/nyfish/Percidae/fantail_darter.html
http://fishbase.org/summary/Etheostoma-flabellare.html

Freshwater Drum (Aplodinotus grunniens)
http://www.fishbase.org/summary/Aplodinotus-grunniens.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Aplodinotus+grunniens

Golden Redhorse (Moxostomata erythrurum)
http://fishbase.org/Summary/speciesSummary.php?ID=3004&AT=golden+redhorse
http://explorer.natureserve.org/servlet/NatureServe?searchName=Moxostomata+erythrurum

Green Sturgeon (Acipenser medirostris)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Acipenser+medirostris
https://www.fishbase.in/summary/2592

Lake Sturgeon (Acipenser fulvescens)
http://www.fws.gov/midwest/sturgeon/biology.htm
http://fishbase.org/summary/Acipenser-fulvescens.html

Lake Trout (Salvelinus namaycush)
https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82519---,00.html
http://www.fishbase.org/summary/Salvelinus-namaycush.html

Lake Whitefish (Coregonus clupeaformis)
https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82676---,00.html
http://fishbase.org/summary/Coregonus-clupeaformis.html

Longnose Dace (Rhinichthys cataractae)
http://explorer.natureserve.org/servlet/NatureServe?searchName=rhinichthys+cataractae
https://www.fishbase.de/summary/2944

Longnose Sucker (Catostomus platyrhynchus)
http://explorer.natureserve.org/servlet/NatureServe?searchName=catostomus+catostomus
https://www.fishbase.de/summary/2962

Mottled Sculpin (Cottus bairdii complex)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Cottus+bairdii
https://fishbase.mnhn.fr/summary/4065

Mountain whitefish (Prosopium williamsoni)
http://explorer.natureserve.org/servlet/NatureServe?searchSpeciesUid=ELEMENT_GLOBAL.2.104696
https://www.fishbase.in/summary/2685

Northern Pike (Esox Lucius)
https://www.michigan.gov/dnr/0,4570,7-350-79135_79218_79614_82648---,00.html
http://www.fishbase.org/summary/258

Pacific Eulachon (Thaleichthys pacificus)
https://fishbase.mnhn.fr/summary/Thaleichthys-pacificus.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Thaleichthys+pacificus

Pacific lamprey (Entosphenus tridentate)
http://explorer.natureserve.org/servlet/NatureServe?searchName=lampetra+tridentata
https://eol.org/pages/46582336

Pumpkinseed (Lepomis gibbosus)
https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/Pumpkinseed.aspx
http://fishbase.org/summary/Lepomis-gibbosus.html

Shortnose sturgeon (Acipenser brevirostrum)
http://www.chesapeakebay.net/fieldguide/critter/shortnose_sturgeon
http://www.fishbase.se/summary/Acipenser-brevirostrum.html

Shovelnose Sturgeon (Scaphirhynchus platorynchus)
http://www.fishbase.org/summary/Scaphirhynchus-platorynchus.html
http://www.iucnredlist.org/details/19943/0

Slimy sculpin (Cottus cognatus)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Cottus%20cognatus
https://fishbase.mnhn.fr/summary/4068

Smallmouth bass (Micropterus dolomieu)
http://fishbase.org/summary/Micropterus-dolomieu.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Micropterus+dolomieu
https://www.chesapeakebay.net/discover/field-guide/entry/smallmouth_bass

Smallmouth Buffalo (Ictiobus bubalus)
http://www.fishbase.se/summary/Ictiobus-bubalus.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Ictiobus+bubalus

Sockeye Salmon (Oncorhynchus nerka)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Oncorhynchus+nerka
https://fishbase.mnhn.fr/summary/243

Spot Croaker (Leiostomus xanthurus)
http://www.chesapeakebay.net/fieldguide/critter/spot
http://fishbase.org/summary/Leiostomus-xanthurus.html

Spottail Shiner (Notropis hudsonius)
https://spo.nmfs.noaa.gov/sites/default/files/legacy-pdfs/leaflet608.pdf
http://fishbase.org/summary/Notropis-hudsonius.html

Steelhead/Rainbow Trout (Oncorhynchus mykiss)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Oncorhynchus+mykiss
https://fishbase.mnhn.fr/summary/239

Striped Bass (Morone saxatilis):
http://www.chesapeakebay.net/fieldguide/critter/striped_bass
http://www.fishbase.org/summary/353

Walleye (Sander vitreus):
http://www.fishbase.org/summary/Sander-vitreus.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Sander+vitreus

White Bass (Morone chrysops):
http://www.fishbase.org/summary/Morone-chrysops.html
http://explorer.natureserve.org/servlet/NatureServe?searchName=Morone+chrysops
https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82599---,00.html

White Perch (Morone americana):
http://www.chesapeakebay.net/blog/post/white_perch_in_the_bay_and_its_rivers
http://www.fishbase.se/summary/Morone-americana.html

White Sturgeon (Acipenser transmontanus)
https://ecos.fws.gov/ecp/species/8241
www.fishbase.org/summary/2594

White Sucker (Catostomus commersonii)
https://www.nrc.gov/docs/ML0708/ML070800423.pd
fhttp://fishbase.org/summary/Catostomus-commersonii.html

Yellow Perch (Perca flavescens)
https://www.michigan.gov/dnr/0,8817,7-350-79135_79218_79614_82677---,00.html
http://www.fishbase.org/summary/Perca-flavescens.html
https://www.fishandboat.com/Fish/PennsylvaniaFishes/Pages/YellowPerch.asp

3.8.2 Invertebrates

American Salmonfly (Pteronarcys dorsata)
http://fieldguide.mt.gov/speciesDetail.aspx?elcode=iiple2v040
http://explorer.natureserve.org/servlet/NatureServe?searchName=Pteronarcys+dorsata

Blue Crab (Callinectes sapidus)
http://www.chesapeakebay.net/issues/issue/blue_crabs
https://irlspecies.org/taxa/index.php?quicksearchselector=on&quicksearchtaxon=Blue+Crab+-+Callinectes+sapidus&taxon=8235&formsubmit=Search+Terms

Burrowing Mayfly (Hexagenia spp.)
https://www.pnas.org/content/pnas/early/2020/01/15/1913598117.full.pdf
https://www.usgs.gov/node/123984

Common Crayfish (Cambarus bartonii)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Cambarus+bartonii
http://www.fws.gov/fisheries/ans/erss/uncertainrisk/Cambarus-bartonii-ERSS-June2015.pdf

Creeper Mussel (Strophitus undulates)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Strophitus+undulatus
http://molluskconservation.org/MUSSELS/Habitat.html

Eastern Oyster (Crassostrea virginica):
http://www.chesapeakebay.net/fieldguide/critter/eastern_oyster
https://irlspecies.org/taxa/index.php?quicksearchselector=on&quicksearchtaxon=Eastern+Oyster+-+Crassostrea+virginica&taxon=4347&formsubmit=Search+Terms

Freshwater Mussel (Elliptio complanata)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Elliptio+complanata
http://molluskconservation.org/MUSSELS/Habitat.html

Freshwater Mussel (Margaritifera falcata)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Margaritifera+falcata
http://molluskconservation.org/MUSSELS/Habitat.html

Freshwater Mussel (Strophitus undulates)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Strophitus+undulatus
http://molluskconservation.org/MUSSELS/Habitat.html

Washboard Mussel (Megalonaias nervosa)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Megalonaias+nervosa
http://www.dnr.state.mn.us/rsg/profile.html?action=elementDetail&selectedElement=IMBIV29020

Zebra Mussel (Dreissena polymorpha)
https://www.greatlakesnow.org/2020/02/zebra-mussels-impact-good-bad/
http://nas.er.usgs.gov/queries/factsheet.aspx?speciesid=5

3.8.3 Plants

Clasping-leaved Pondweed (Potamogenton perfoliatus)
http://www.issg.org/database/species/ecology.asp?si=902&fr=1&sts=tss&lang=EN
https://www.nrcs.usda.gov/Internet/FSE_PLANTMATERIALS/publications/mdpmcfs10163.pdf

Eelgrass (Zostera marina)
http://www.chesapeakebay.net/issues/issue/bay_grasses#inline
http://www.seagrassli.org/ecology/eelgrass/taxonomy.html

Northern Water-milfoil (Myriophyllum sibiricum)
http://explorer.natureserve.org/servlet/NatureServe?searchName=Myriophyllum+sibiricum

Widgeongrass (Ruppia maritima)
https://dnr.maryland.gov/waters/bay/Documents/SAV/widgeon_grass.pdf
https://pubs.er.usgs.gov/publication/2000099 (PDF: *handle.dtic.mil/100.2/ADA322676*)

Wild Celery (Vallisneria americana)
https://www.dnr.state.mn.us/aquatic_plants/submerged_plants/wild_celery.html

3.8.4 Planktonic Organisms

Amphipod (Diporeia spp.)
http://www.glerl.noaa.gov/pubs/fulltext/2005/20050005.pdf
http://www.glerl.noaa.gov/res/Task_rpts/1998/edybrandt09-3.html

Copepod *(Acartia tonsa)*
http://www.vims.edu/GreyLit/VIMS/ssr115.pdf

Copepod (Daphia spp.)
http://www.ncbi.nlm.nih.gov/books/NBK2042/

Cyanobacteria (Microcycstis aeruginosa)
https://www.calverthealth.org/healththreats/healthhazards/microcystis.htm
http://www.algaebase.org/search/species/detail/?species_id=30050

Cyanobacteria (Microcycstis aeruginosa)
http://www.algaebase.org/search/species/detail/?species_id=30050

Dinoflagellate *(Prorocentrum minimum)*
http://species-identification.org/species.php?species_group=dinoflagellates&id=93

Opossum Shrimp (Mysis relicta)
https://www.glerl.noaa.gov/library/annual/2002/2002-04.pdf
http://people.cst.cmich.edu/mcnau1as/zooplankton%20web/Mysis/Mysis.html

Scud (Gammarus fasciatus)
http://people.cst.cmich.edu/mcnau1as/zooplankton%20web/Gammarus/Gammarus.htm

4.0 Technical Resources

The analysis of thermal discharges can require data-intensive methods to predict the extent of thermal plumes, gather sufficient data, and to select appropriate mitigation strategies.

This chapter provides a summary of frequently used hydrodynamic models to study thermal plumes, mixing zones and other hydrological and water quality conditions. This chapter also provides a summary of tools and approaches for monitoring temperature. Lastly, this chapter provides a review of technologies and operational strategies to mitigate thermal discharges.[19]

4.1 Thermal Mixing Model Review

4.1.1 Introduction

Climate change is likely to modify the temperature of receiving waters for permitted discharges across much of the United States. Already, some EPA regions are documenting increased incidence of thermal discharge exceedances downstream of permitted discharge points. In a changing climate, there is a need to supplement existing CWA Section 316(a) documentation and to provide updated tools for both regulators and dischargers to inform the process by which 316(a) variances are evaluated.

This section reviews five hydrodynamic models and their applicability to modeling thermal mixing in waterbodies downstream of point source discharges. The goal is to provide a concise summary of these models, so that they can be further evaluated for potential use in Section 316(a) permitting and thermal mixing in a changing climate. Section 4.1.2 provides an overview of model selection. Sections 4.1.3 through 4.1.7 summarize the development history, components and processes, inputs, outputs, and limitations and advantages for several thermal discharge models. Section 4.1.8 provides general background information regarding hypothetical discharge scenarios based on changes in climate and hydrology that are likely to affect Section 316(a) demonstration studies and thermal mixing downstream of point source discharges. Section 4.1.9 presents a summary of the models.

4.1.2 Model Selection

EPA began model selection by compiling a list of available models that simulate temperature in waterbodies. EPA compiled the list of models from relevant literature, surface models listed on EPA's website (http://www.epa.gov/exposure-assessment-models/surface-water-models), and suggestions from EPA staff and expert water modelers. From the list of available models, five models were selected for further evaluation.

The final set of models was selected by excluding all 1-D models, considering recent model usage, taking into account the availability of technical support, consulting with EPA staff, and including both commercial and publicly available models. In addition, the models were selected based on their capacity to collectively model the full range of potential receiving waterbodies for thermal discharges (e.g., rivers, reservoirs, lakes, estuaries, and coastal environments). Finally, models were evaluated based on

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[19] See disclaimer on page iii. EPA also notes that the discussion of models and equipment in this section is not intended to be comprehensive. Reasonable effort was made to capture information on the most commonly and widely applied tools in the industry, but this document is not intended to be an exhaustive inventory of all applications. To submit information on additional thermal models or monitoring tools, please contact EPA.

their near-field and far-field modeling capabilities, and the set of models was selected to include at least one model with robust near-field modeling capabilities (i.e., CORMIX). CORMIX can be coupled with far-field models lacking dedicated outfall modeling capabilities to provide a more wholistic view of discharge impacts on a waterbody. The five models selected for detailed evaluation are listed in Table 4-1.

Table 4-1. List of models compiled for potential review.

Model	Developer
CORMIX	MixZon, Inc. (MixZon)
EFDC	Tetra Tech, Inc.
Delft3D	Deltares
CE-QUAL-W2	Portland State University
MIKE 3	Danish Hydraulic Institute (DHI)

Although EPA reviewed five models below in detail, this is not intended to be an exclusive list of applicable models for simulating thermal mixing. Other models not reviewed here may be equally appropriate, or more appropriate, for a specific mixing evaluation due to site-specific characteristics.

For detailed technical information about how each model works, its input data needs, and model outputs, refer to Appendix C at the end of this section.

4.1.3 CORMIX version 12.0 (January 2021)

CORMIX simulates discharge plume geometry and dilution in both near- and far-field zones. CORMIX can be applied to discharges in many different waterbodies, such as rivers, lakes, and estuaries. Originally a freely available model, CORMIX has been commercial since 2002 when MixZon began updating the model. It has been widely utilized in thermal mixing studies.

Development

CORMIX was originally developed in 1990 by Cornell University for the EPA (CORMIX, 2021a). Cornell released multiple open-source versions and additional subsystems to CORMIX (CORMIX1, CORMIX2, and CORMIX3) until 1996 (Jirka et al., 1996). Oregon Graduate Institute released versions 4.0 and 4.1 in 1999 and 2000, respectively. In 2002, MixZon became the developer, releasing CORMIX version 4.2. The current version of CORMIX, version.12.0, was released by MixZon in January 2021.

Scope and Applications of Model

CORMIX is designed to simulate plume conditions in a mixing zone, downstream of point source discharge systems (Durkee, 2012). CORMIX is best suited for modeling thermal plume dynamics in the near-field and the intermediate zone (e.g., zero to a few hundred meters downstream), but it can also model far-field dilution characteristics (Morelissen et al., 2013). CORMIX can simulate mixing from different types of outfalls such as single port outfalls and multi-port diffusers in varied configurations. CORMIX is widely used in near-field thermal modeling (Schreiner et al., 1999; Durkee, 2012; Morelissen et al., 2013; ODEQ, 2013) and has been successfully coupled with far-field models, such as Delft3D or MIKE 3, to provide more accurate near- and far-field plume simulation results (Morelissen et al., 2013).

Users can apply CORMIX to model point source discharge thermal mixing in rivers, lakes, estuaries, and coastal receiving waters (CORMIX, 2021b).

Applicability to Thermal Mixing Studies - Advantages and Limitations

CORMIX has been used extensively for modeling thermal mixing. Many articles and studies can be found at CORMIX's website: http://www.cormix.info/validations.php. CORMIX has been applied in mixing zone simulations in the United States as well as abroad: North Carolina and Idaho (CORMIX, 2021h), Maryland (Schreiner et al., 1999), the Great Lakes (Tsanis et al., 1994), and South Korea (Kang et al., 2000). CORMIX has been used in 316(a) demonstration projects for decades. Examples include the Sammis generating plant on the Ohio River (EA, 1992); nearfield modeling conducted for the Cook Plant Thermal Plume Study in Lake Michigan (Limno-Tech Inc., 2000) and Black Dog Generating Plant discharge into the Minnesota River (Xcel Energy, 2007).

Advantages and Strengths

- CORMIX is the only available tool among the models reviewed for detailed thermal mixing analysis of point source discharges through outfalls, including multiport diffuser outfalls.
- CORMIX is best suited to modeling mixing zones in the near-field and intermediate zones and has successfully been combined with far-field models (Morelissen et al., 2013).
- CORMIX has multiple subsystems that can model different outfall designs. CORMIX1 and CORMIX2 can model positively, neutrally, or negatively buoyant discharge. Accordingly, CORMIX can be applied to model mixing zones under a wide range of discharge system designs and receiving waters (Doneker and Jirka, 2007).
- The model includes boundary interactions, which allows CORMIX to determine the near-field mixing zone's discharge stability (CORMIX, 2021i).
- The model is being actively supported by the developer and receives regular updates and bug-fixes.

Limitations

- CORMIX is best suited to modeling point source discharges in the near-field and does a poorer job with far-field plumes. (It can be coupled with other models, such as Delft3D (Morelissen et al., 2013) to adequately model both near- and far-field plumes).
- Each subsystem (CORMIX1, CORMIX2, and CORMIX3) has discharge geometry restrictions and limitations, such as port height and port diameter, which are defined in the user manual (Doneker and Jirka, 2007).

Model Contacts and Documentation

- CORMIX can be downloaded at: http://www.mixzon.com/downloads/
- CORMIX training is available at: http://www.mixzon.com/training/
- CORMIX articles can be found at: http://www.cormix.info/references.php
- CORMIX validation studies are located at: http://www.cormix.info/validations.php
- CORMIX applications are described at: http://www.cormix.info/applications.php

Model Summary

CORMIX is capable of modeling both near- and far-field thermal plume behaviors. CORMIX is no longer freely available, but users can download a trial from MixZon to familiarize themselves with the model. The cost of a one-year single computer license for a consultant is $3,799. Costs may vary depending on the number of licenses purchased and the purpose of the license (i.e., research and education, consulting, or regulatory). Dischargers can use CORMIX to design outfall systems or to model mixing zone plumes from single port and multiport outfalls. The GUI and output tools, in combination with the training and technical support that MixZon provides, help clients maximize CORMIX modeling utility. Because CORMIX is strong at modeling near-field mixing zones, it has been successfully coupled with models designed to model far-field plume dynamics (e.g., Delft3D-FLOW, MIKE 3). Although CORMIX has been successfully applied to many thermal mixing studies, its limitations in modeling far-field dynamics suggest that dischargers should consider coupling CORMIX with far-field models to help increase model utility.

CORMIX Version 12.0 References

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CORMIX. 2021a. CORMIX Development history. Available: http://www.cormix.info/devhistory.php Accessed October 4, 2021.

CORMIX. 2021b. CORMIX1: Single Port Discharges. Available: http://www.cormix.info/CORMIX1.php. Accessed October 4, 2021.

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CORMIX. 2021d. CORMIX3: Surface, Shoreline Discharges. Available: http://www.cormix.info/CORMIX3.php. Accessed October 4, 2021.

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CORMIX. 2021g. CORMIX Hints for Use. Available: http://www.mixzon.com/docs/UserManuals/CORMIX_UM/CORMIX_UserManual/. Accessed: October 28, 2021.

CORMIX. 2021h. CORMIX Mixing Zone Applications. Available: http://www.cormix.info/applications.php. Accessed October 4, 2021.

CORMIX. 2021i. CORMIX Methodology. Available: http://www.cormix.info/methodology.php. Accessed October 4, 2021.

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ODEQ. 2013. Regulatory Mixing Zone Internal Management Directive. Part Two: Reviewing Mixing Zone Studies. Oregon Department of Environmental Quality (OR DEQ).

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Tsanis, I.K., C. Valeo, and Y. Diao. 1994. Comparison of Near-Field Mixing Models for Multiport Diffusers in the Great Lakes. Canadian Journal of Civil Engineering, Vol. 21. Feb. 1994.

Xcel Energy. 2007. Black Dog Plant 316(a) Demonstration Environmental Study. Xcel Energy Environmental Services Department.

4.1.4 Delft3D v6.03 (June 2021)

Delft3D is a modeling package that allows users to simulate flow, sediment transport, water quality in a range of waterbodies. Delft3D-FLOW is the hydrodynamic module in the Delft 3D package that applies to thermal modeling. It is best suited to model far-field zones and can be applied to rivers, lakes, reservoirs, estuaries, and coasts. Delft3D-FLOW is a freely available open source model; users must register with the developer, Deltares, to download the model and obtain technical help.

Development

Delft3D was created by Deltares and has been freely available since 2011 (Deltares, 2021a). The hydrodynamic module, Delft3D-FLOW, is designed to simulate flow and far-field characteristics (Deltares, 2021b). The Delft3D FM (Flexible Mesh) Suite is a finite element companion software developed by Deltares which can be used to create mesh networks for coastal, estuarine, and river receiving water environments (Deltares, 2021c).

Scope and Applications of Model

Delft3D modules are used to model discharges into rivers, lakes, reservoirs, coasts, and estuaries (Morelissen et al., 2013; Deltares, 2021b). Delft3D-FLOW is a far-field thermal model, but it has been successfully coupled with near-field models such as CORMIX (Morelissen et al., 2013).

Applicability to Thermal Mixing Studies - Advantages and Limitations

Advantages and Strengths

- Delft3D has a flexible grid system to simulate thermal mixing in complex waterbodies.
- Delft3D-FLOW is publicly available and offers training and other resources to help users become familiar with the module or entire Delft3D package.
- Delft3D has strong capabilities for hydrodynamics (Shoemaker et al., 2005)
- Delft3D is widely used by the modeling community. The Deltares website has links to two databases with 8,500 Delft3D articles (Deltares, 2021e).
- The model is being actively supported by the developer and receives regular updates and bug-fixes.

Limitations

- Because the immediate effect of buoyancy on vertical flow is not considered by Delft3D-FLOW, the application of Delft3D-FLOW is restricted to mid-field and far-field dispersion simulations of discharged water (Deltares, 2021b).
- The model assumes no heat loss through the bottom of the model domain (Deltares, 2021b). Heat flux through the water surface must be simulated with a specified temperature model, some of which may have limitations.

Model Contacts and Documentation

- Delft3D-FLOW can be downloaded at: https://oss.deltares.nl/web/delft3d/downloads
- Delft3D-FLOW training is provided at: http://oss.deltares.nl/web/delft3d/webinars
- Delft3D-FLOW validation studies are available at: http://oss.deltares.nl/c/document_library/get_file?uuid=39169f8f-4ab0-4f7b-9771-c3f7d0ddd61f&groupId=183920

Model Summary

Delft3D-FLOW is a mid-field to far-field, publicly available model. It is available at no cost upon registering on the Deltares website. Delft3D-FLOW has a GUI for assembling model inputs that simplifies simulation preparation. Deltares also offers webinars and other training help on their website. Because Deflt3D-FLOW is a mid- to far-field model, it has been coupled with CORMIX to model the near-field and intermediate zones downstream of a discharge point. The Delft3D package has been widely used for both research and private sector work, as evidenced by the availability of 8,500 Delft3D articles in the scientific literature (Deltares, 2021e). Users can maximize the Deflt3D-FLOW module utility because it has a GUI that helps users create inputs, a GPP that helps users visualize and animate results, and strong training and product support.

Delft3D v6.03 References

Deltares. 2021a. About Delft3D. Available: https://oss.deltares.nl/web/delft3d/about. Accessed October 4, 2021.

Deltares, 2021b. Deflt3D-FLOW: Simulation of Multi-Dimensional Hydrodynamic Flows and Transport Phenomena, including Sediments User Manual. September 27.

Deltares. 2021c. Delft3D Flexible Mesh Suite. Available: https://www.deltares.nl/en/software/delft3d-flexible-mesh-suite/#7. Accessed October 4, 2021.

Deltares. 2021d. *Delft3D-GPP User Manual*. 6.03 editions. Deltares, Delft, Netherlands.

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4.1.5 Environment Fluid Dynamics Code (EFDC) v1.01 (September 2007)

The EFDC was created with the support of EPA. EFDC can simulate both near- and far-field thermal mixing and can be applied to rivers, lakes, reservoirs, estuaries, and coasts. The model is freely available and has been used in thermal mixing studies and Section 316(a) demonstration studies throughout the United States.

Development

EFDC was originally developed at the Virginia Institute of Marine Science in 1988. Tetra Tech took over model development and maintenance in 1996 with support from the EPA (Hamrick, 2007a). The most current version, EFDC v1.01, was released in September 2007 (U.S. EPA, 2015) by Tetra Tech and is described in several publications by developer John Hamrick (Hamrick, 2007a, 2007b, 2007c). This report discusses the features of the EPA-released EFDC v1.01; however, a number of consulting firms and government agencies have developed proprietary EFDC extensions and customized versions of the software. Two private firms, Tetra Tech and DSI, LLC, have developed proprietary EFDC versions which add graphical user interfaces and other usability features to EFDC. In addition, the St. Johns Water Management District in Florida maintains a version of EFDC which has been customized for the St. Johns River (U.S. EPA, 2018).

Scope and Applications of Model

EFDC has a single port jet module to model near-field thermal mixing (U.S. EPA, 2007) nested within a 3-D hydrodynamic model, so it can also be applied to simulate both near-field and far-field thermal mixing. The single port assumption may be a substantial limitation for the near-field analysis since many facilities discharge through multi-port diffusers. It has been applied to many waterbodies including rivers, lakes, reservoirs, estuaries, and coasts (Shoemaker et al., 2005). EFDC is a publicly available model that is supported by the EPA (Hodge et al., 2011). The model has been used to simulate thermal plumes in mixing zones since at least the early 1990s (Hamrick, 2007a).

Applicability to Thermal Mixing Studies - Advantages and Limitations

EFDC has been applied to many waterbodies to simulate thermal mixing and has been used for more than 100 modeling studies (U.S. EPA, 2020). It has been used to investigate the mixing zone downfield of cooling water discharged to Lake Michigan in Whiting, Indiana (Hodge et al., 2011) and at the Point Beach Nuclear Plant in Lake Michigan (EA, 2008). The EFDC model has also been applied to estuaries such as Chesapeake Bay and Stephens Passage, Alaska (Shoemaker et al., 2005).

Advantages and Strengths

- EFDC can simulate complex hydrodynamics in thermal modeling downstream of point source discharge.
- EFDC can simulate rivers, lakes, reservoirs, estuaries and coastal environments (Shoemaker et al., 2005).
- EFDC can simulate mixing in 1-D, 2-D, and 3-D.
- EFDC has been widely applied and validated (U.S. EPA 2007).
- The single port buoyant jet module allows for both near and far field mixing analysis (U.S. EPA 2007).

Limitations

- The 2007 version does not have a GUI or pre- or post-processing.
- There is no current federally funded support program to maintain or support the model. However, various government, academic, and consulting firms maintain privately distributed model software based on EFDC.

Model Contacts and Documentation

- EFDC can be downloaded at: https://www.epa.gov/ceam/environmental-fluid-dynamics-code-efdc.

Model Summary

EFDC is a freely available model that has simulated thermal mixing since the 1990s. It can be applied to most waterbody types and is able to model complex bathymetry. Simulations can be run in 1-D, 2-D, or 3-D and can include point source pollution discharge. EFDC can model thermal mixing in both near- and far-field zones.

EFDC References

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4.1.6 MIKE 3 FM (MIKE 3 2021 release)

MIKE 3 FM is a commercial (proprietary) model created by the DHI as a component of the MIKE 3 series of modeling tools. MIKE 3 FM can be applied to lakes and reservoirs to model thermal mixing, but it was specifically designed to model coastal areas.

Development

DHI Water and Environment created the MIKE model, initially released in 1996. The latest version of MIKE 3 FM was released as part of the MIKE 2021 package at the end of 2020 (MIKE, 2020).

Scope and Applications of Model

MIKE 3 FM is used to model hydrologic conditions for discharge to stratified waters in coastal areas and lakes (Moharir et al., 2014, DHI, 2021a) and is applicable to thermal modeling of stratified environments. MIKE 3 FM is capable of modeling both near-field and far-field receiving water environments for a discharge (DHI, 2021a). It is capable of simulating discharges from a variety of types of outfall types including, but not limited to, turbines, weirs, culverts, and dikes (DHI, 2021a).

Applicability to Thermal Mixing Studies - Advantages and Limitations

Advantages and Strengths

- DHI provides strong product support, individualized help, and online help tools.
- Users have the ability to select and purchase only the modules that are needed for their site.

- MIKE 3 FM can simulate complex receiving waterbody environments and integrates both near-field and far-field simulations.
- The software is being actively supported by the developer and receives regular updates and bug-fixes.

Limitations

- The model is not applicable to rivers; however, DHI also produces other software platforms which are better suited to these waterbodies.
- The model is expensive to purchase.

Model Contacts and Documentation

- MIKE 3 FM can be downloaded at: https://www.mikepoweredbydhi.com/download/mike-2021
- MIKE 3 FM training is provided at: https://www.theacademybydhi.com/training
- MIKE 3 FM articles are located at: https://www.theacademybydhi.com/

Model Summary

Because MIKE 3 FM contains modules that the user can buy individually, the cost of the model varies depending on the user needs. DHI distributes MIKE 3 FM in various forms: subscription packages, perpetual licenses, and cloud-based metered (i.e., per-hour) packages (MIKE, 2021). A single annual subscription to the Marine GO package—which includes MIKE 3 FM, and a bonus module—is available for $6,360 per year (DHI, 2021b). Costs may vary depending on the number of licenses purchased and the purpose of the license (i.e., research and education, consulting, or regulatory).

MIKE 3FM References

DHI. 2020. Release Note 2021. DHI, Denmark. Available: https://manuals.mikepoweredbydhi.help/2021/Release_Notes/MIKE%203%20Release%20Notes.pdf Accessed October 13, 2021.

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4.1.7 CE-QUAL-W2 v4.5 (August 2021)

CE-QUAL-W2 is a freely available model that is derived from the Laterally Averaged Reservoir Model (LARM), which was created in the 1970s. It can simulate thermal mixing in rivers, lakes, reservoirs, and estuaries. Generally, CE-QUAL-W2 is applied to far-field modeling.

Development

The CE-QUAL-W2 model derives from LARM, which was developed by Edinger and Buchak and released in 1975. Version 1.0 of CE-QUAL-W2 was released in 1986 by the U.S. Army Corps of Engineers Waterways Experiment Station (Water Quality Research Group, 2015). The most recent version, CE-QUAL-W2 v4.5, was released in August 2021 by Portland State University (Wells, 2021) and is publicly available for download.

Scope and Applications of Model

CE-QUAL-W2 is a 2-D (laterally averaged) model that can be applied to rivers, lakes, reservoirs, and estuaries (Shoemaker et al., 2005), but is best suited for long and narrow waterbodies because it assumes lateral homogeneity (Wells, 2021). The model is generally applied to simulate far-field thermal mixing. The model does not include an outfall discharge module, and the lateral averaging is a significant limitation for discharge plume assessment. While not appropriate for use in all waterbodies, a 2-D model of this type will be of best use in streams and rivers where outfall diffusers have been installed to achieve rapid and complete mixing of a thermal discharge with the waterbody, or where other circumstances cause discharges to be well-mixed across the waterbody width. The model is widely used in the United States, particularly for total maximum daily load (TMDL) studies (Irvine et al., 2005).

Applicability to Thermal Mixing Studies - Advantages and Limitations

CE-QUAL-W2 has been applied to many waterbodies in the Unites States (Irvine et al., 2007). It has been used in lakes (Hanna et al., 1999; Boegman et al., 2001) and streams (Martinez et al., 2014) to determine appropriate temperature controls. The model can be used to simulate thermal mixing within rivers, lakes, reservoirs, and estuaries, where assumptions of lateral homogeneity are appropriate.

Advantage and Strengths

- CE-QUAL-W2 can be applied to branching waterbodies.
- Users can vary grid spacing to change spatial resolution as needed, so the model can simulate complex waterbodies (Irvine et al., 2005).
- The model is being actively supported by the developer and receives regular updates and bug-fixes.

Limitations

- The model does not include an outfall discharge module, and the 2-D lateral averaging is a significant limitation for discharge plume assessment.
- CE-QUAL-W2 assumes lateral homogeneity; i.e., that lateral variations in velocity and temperature can be ignored (Wells, 2021). It also assumes homogeneity within vertical model layers. It is thus only appropriate for waterbodies that are much longer than they are wide. This assumption may not be appropriate in large waterbodies where assumptions of lateral and layer homogeneity do not apply.

- Despite being a 2-D model, CE-QUAL-W2 is capable of incorporating branching waterbody tributary segments which are oriented orthogonally to the main waterbody segments—this yields a quasi-3D model segment organizational capability.

Model Contacts and Documentation

- CE-QUAL-W2 can be downloaded at: http://www.cee.pdx.edu/w2/download.html; http://www.cee.pdx.edu/w2/
- CE-QUAL-W2 training is provided at: https://www.pdx.edu/civil-environmental-engineering/water-quality-modeling-workshops
- CE-QUAL-W2 validation studies at: http://www.cee.pdx.edu/w2/

Model Summary

CE-QUAL-W2 has a long history of modeling water quality and temperature in various waterbodies within the United States, particularly for TMDL studies. The model is open source, so it can be downloaded at no cost to the user. Although CE-QUAL-W2 is generally applied as a far-field model, it does have the capability to define discharge inputs into the simulation. CE-QUAL-W2 is a 2-D model and although it can be applied to most waterbodies, it is best-suited to simulate plumes in waterbodies that are long and narrow in shape because of the assumption of lateral homogeneity embedded in the model equations.

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4.1.8 Climate Change Considerations for Thermal Mixing Models

The sections above describe various models that could be applied to evaluate the effect of discharges on the ambient temperature in receiving waterbodies in a variety of environmental settings. To evaluate thermal mixing in these waterbodies, these models should consider the range of expected temperature and flow conditions from both the point source discharge and within the receiving water. Site-specific historical flow and temperature data for a waterbody provide a useful range to develop model input parameters, but these data do not account for potential changes in flow or water temperature resulting from climate change. Thus, the historical record may not be sufficiently representative of future conditions to inform 316(a) demonstration projects under a changing climate.

Changes in climate are projected to result in rising global air temperatures, as well as changes in the distribution, frequency and magnitude of precipitation events. Across the continental United States, average surface temperature has risen at an average rate of 0.16°F per decade since 1901. Since 1979, the average rate temperature increase has risen to 0.31 to 0.54°F per decade (U.S. EPA, 2021). Waterbody temperatures will generally increase in response to increases in air temperature (Mohseni and Stefan 1999; Mohseni et al., 2003; Isaak et al., 2011), but site-specific factors such as groundwater inputs, snowmelt, surface impoundments, and shading of waterbodies from vegetation will locally influence the relationship between air temperature and water temperature (e.g., Arismendi et al., 2014).

Projected changes in precipitation are much more uncertain than changes in temperature across major climate models (e.g., Walsh et al., 2014). Increasing air temperatures are also likely to alter snow accumulation and snowmelt timing, changing the pattern of both flow and temperature in snowmelt dominated stream systems. Recent work has already observed that peak streamflows are arriving earlier in the water year (e.g., Stewart et al. 2005; Hall et al., 2015) and snowpack is diminished throughout most of the Western United States as more precipitation falls as rain rather than snow (e.g., Knowles et al., 2006). These changes in the timing, magnitude and form of precipitation are likely to create significant changes in future streamflow, but the uncertainties in these projections are substantial.

All of these uncertainties make it difficult to develop precise estimates of future flow and temperature conditions for any particular receiving water without a substantial data collection and computational effort (e.g., Das et al., 2013; Loinaz et al., 2013; Wobus et al., 2015). Recognizing these limitations, however, there may be some value in developing scoping-level assessments of climate change impacts and superimposing these changes onto historical data to inform future flow and temperature conditions. Below are some suggested methods for these scoping-level climate change impact studies. Note, however, that these methods should be used only to create first-order estimates of future conditions, and to inform what level of site-specific modeling might be required.

Site-specific, monthly projections of air temperature changes are available through a number of data portals. One of these is the climate resilience evaluation and awareness tool (CREAT), developed by the EPA as part of their Climate Ready Water Utilities program (http://www.epa.gov/crwu). The datasets available through CREAT bracket the range of future temperatures for each region in the United States by selecting the “hot”, “cool” and “middle” models across all of the models in the fifth coupled model inter-comparison project (CMIP5). Using simplified air temperature-water temperature relationships such as those developed by Mohseni and colleagues (Mohseni and Stefan, 1999; Mohseni et al., 2003), these monthly changes in air temperature could be translated into projected changes in water temperature, and superimposed onto historical data to bracket future stream temperatures at a site.

As described above, climate change impacts on flow are substantially more uncertain than impacts on temperature, both because of intermodel uncertainty and because changes in flow will depend on how a given change in precipitation is downscaled and routed across a complex land surface (e.g., Mendoza et al., 2015; Mizumaki et al., 2016). As a result, there are few datasets available that can inform changes in flow at any site of interest. Such datasets are being developed, however, as climate science is a rapidly evolving field. For example, the U.S. Bureau of Reclamation (USBR) (2014) developed hydrologic projections that incorporate climate change (CMIP3 and CMIP5).[20] Eventually, these data could be queried to estimate local changes in the frequency or magnitude of the low flow events that would be of most relevance to Section 316(a) demonstration studies. As with changes in temperature, any such changes in flow should be used only for scoping-level assessments of how flow conditions might change in the future.

Once future flow and temperature scenarios have been developed, any of the models reviewed could, in principle, be used to model future thermal conditions in receiving waters. It is likely that uncertainties arising from the choice of thermal mixing model will be small compared to uncertainties in the climate projections for most sites.

4.1.9 Summary of Model Review

This section summarizes the development history and features of five models that are capable of simulating thermal mixing in a variety of waterbodies. Table 4-2 summarizes the primary characteristics of these models. All five of the models are capable of 2-D or 3-D simulations. However, each model has strengths and weaknesses relative to one another, so it is up to the user to determine which model is most applicable to model thermal mixing at a given site.

CORMIX is often used to perform initial site characterizations, for near-field portions of thermal modeling (Hodge et al., 2011). Results from CORMIX simulations are often used to determine plume length, define input variables, or investigate site characteristics to inform other models such as Delft3D, EFDC, CE-QUAL-W2, and MIKE3 (Hodge et al., 2011; Morelissen et al., 2013). EFDC can simulate both near-field and far-field plumes and has been applied to thermal mixing simulations at hydrodynamically and geometrically complex sites (Hodge et al., 2011).

CORMIX, and EFDC have been applied in the 316(a) example demonstration studies provided to us by EPA. Although Delft3D, CE-QUAL-W2 or MIKE3 were not used in the example studies, these studies would only encompass a subset of the studies that have been performed. All five of the reviewed models are suitable for potential use in Section 316(a) permitting and thermal mixing. However, the characteristics of the site should influence the selection of a thermal mixing model. CORMIX is most

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[20] Note that CMIP6 is the current version of the model. Please refer to https://toolkit.climate.gov/tool/downscaled-cmip3-and-cmip5-climate-and-hydrology-projections and, more generally, https://toolkit.climate.gov/tools for more information.

appropriate for hydrodynamically simplistic sites (Hodge et al., 2011). CE-QUAL-W2 is a 2-D model and should be applied only to limited situations where assumptions of lateral mixing across the waterbody are appropriate, such as long waterbodies (Wells, 2021). Delft3D, EFDC, and MIKE3 are capable of simulating more complex and heterogeneous waterbodies, but may require more user skill and computational effort.

The most recent version of the EFDC model dates from 2007. This model appears to be less supported than models in active development such as CORMIX, Delft3D, CE-QUAL-W2 and MIKE3. CORMIX and MIKE3 must be purchased, while the other three models are in the public domain and freely available.

Table 4-2. Summary of Model Review for Thermal Mixing Studies

Model Name	Developer/ Organization	Current Version	Release date (latest version)	Operating system	Models or tool for thermal mixing	Open Source	Cost	Model type
CORMIX	MixZon	Version 12	2021	Windows	CORMIX1, CORMIX2, CORMIX3 DHYDRO	Commercial	$3,800/license	Finite difference model
Delft3D	Deltares	Version 6.03	2021	LINUX, Windows	Delft3D-FLOW	Freely available	NA	Finite difference model
EFDC	Tetra Tech	Version 1.01	2007	Windows	NA	Freely available	NA	Finite difference model
MIKE 3 FM	DHI	MIKE 2021 package	2021	Windows, Cloud-based	NA	Commercial	$6,400/user/year	Finite difference model
CE-QUAL-W2	Portland State University	Version 4.5	2021	Windows	NA	Freely available	NA	Finite difference model

Table 4-2. (continued) Summary of Model Review for Thermal Mixing Studies

Model Name	Dimensions	Field	Waterbody	Comments	Available for download
CORMIX	2-D, 3-D	Near- and Far-field	Rivers, lakes, reservoirs, estuaries, and coasts	Has been coupled with Delft3D FLOW to model far-field mixing	http://www.mixzon.com/downloads/
Delft3D	2-D, 3-D	Far-field	Rivers, lakes, reservoirs, estuaries, and coasts	Has been coupled with CORMIX for near-field thermal mixing	https://oss.deltares.nl/web/delft3d/downloads
EFDC	1-D, 2-D, 3-D	Near- and Far-field	Rivers, lakes, reservoirs, estuaries, and coasts		http://www2.epa.gov/exposure-assessment-models/environment-fluid-dynamics-code-efdc-download-page
MIKE 3 FM	2-D, 3-D	Near- and Far-field	Lakes, reservoirs, coasts		https://www.dhigroup.com/global/news/2020/11/mike-2021-is-here
CE-QUAL-W2	2-D	Near- and Far-field	Rivers, lakes, reservoirs, and estuaries	Can only model near-field if diffusor is along the channel width	http://www.ce.pdx.edu/w2/download.html

Glossary

Boundary interactions – refers to plume interactions with boundaries such as the banks, bottom, or water surface.

Far-field – the zone of receiving waters downstream of the discharge, where receiving water conditions dominate the mixing mechanisms.

Finite difference method – a numerical method used in computer models to solve the differential equations that describe physical processes such as flow by approximating them with difference equations

Finite element method – a numerical method used in computer models to approximate the differential equations that describe physical processes such as flow by subdividing the model domain into smaller parts called elements, and minimizing an associated error function.

Graphical user interface (GUI) – interface that allows users to interact with the models through visual cues and graphical icons

Intermediate zone – the transitional zone between the near-field and far-field zones, where the forces that dominate mixing change from effluent driven to receiving water driven processes.

Length scale – a measure of the relative effects of hydrodynamic processes on plume mixing.

Multiport outfall – point source discharge incorporating more than one discharge port or nozzle. The nozzles are closely spaced and inject effluent into the receiving waterbody.

Near-field – the zone of receiving waters immediately downstream of the discharge outfall. The size or distance of the near-field zone varies but is classified as the area where the outfall designs and effluent conditions dominate mixing mechanisms.

Negatively buoyant discharge – discharge that is denser than the receiving waters and therefore persists in the lower portion of the receiving water profile unless mixing occurs.

Neutral discharge – discharge that is the same density as the receiving waters and therefore does not persist on the surface or lower portions of the receiving water profile.

Positive or buoyant discharge – discharge that is less dense than the receiving waters and therefore persists in the upper layers of the receiving water profile unless mixing occurs.

Receiving water – defined as the waterbody to which the point source discharge expels. It can be a lake, reservoir, river, estuary, or sea.

Single port outfall – point source discharge with only one discharge nozzle that injects effluent into the receiving waterbody.

Steady state – condition where the discharge and receiving water input parameters do not change over time. Many models assume that receiving water conditions (such as flow or temperature) do not change over the period of time simulated, which is steady state.

Stratification profiles – refers to specified or defined density layering of the receiving waters from top to bottom.

Stratified – refers to receiving water conditions that are layered and not uniform throughout the water column.

Unsteady state – condition where the discharge and receiving water input parameters change over time. Unsteady state models can incorporate changes, such as tides or winds, which affect receiving water or discharge flow.

Unstratified – refers to receiving water conditions that are uniform throughout the water column.

Summary of Model Review References

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4.2 Thermal Monitoring Tools and Implementation

4.2.1 Introduction

Temperature affects virtually all biota and biologically-mediated processes, chemical reactions (notably the dissolution of oxygen), and structures the physical environment of the water column. Thermal impacts due to facility discharges, non-point sources, or regional climate change can result in alterations of ambient temperature, shifts in local patterns, displacement or disruption of seasonal regimes, and degradation of aquatic habitat quality. Our ability to detect, monitor, and respond to temperature change relies upon accurate and timely measurement of water temperature, dependable data collection and storage, and ultimately, quick and easy access to the data for modeling, interpretation, and displays.

This section consists of:

- **Section 4.2.2**: A review of the range and specifications of current tools and methodologies used for *in-situ* (local) thermal monitoring, with data collection summarized in Table 4-3.
- **Section 4.2.3**: A review of the range and specifications of current tools and methodologies used for remote thermal monitoring, with data collection summarized in Table 4-4.
- **Section 4.2.4**: Examples of thermal monitoring systems used to support Section 316(a) demonstrations or thermal mixing zone projects. In addition, an example of the use of TIR imagery to address variability in temporal (e.g., diurnal, seasonal, and annual) and spatial complexity (e.g., for identifying potential cold water refugia in smaller streams where groundwater inputs or hyporheic flows are important components of the streamflow).

These sections are intended to address the wide range of technologies available, applicability and costs of different technologies, and their utility for different receiving waterbody types. [21]

4.2.2 In-situ Thermal Sensors

This section provides an overview of various *in-situ* (i.e., immersed) temperature sensing equipment and systems ranging from hand-held meters to networks of fixed thermistors,[22] thermistor arrays and distributed temperature sensing (DTS) systems. These types of sensors can be used for one-time temperature monitoring events, or they can be left in the field to collect temperature data over variable periods of time.

The following subsections discuss the advantages and disadvantages of the different types of sensors, what type of waterbodies the sensors are best suited for, and the sensors' capabilities for short-term and long-term thermal monitoring programs. This document also describes data loggers for collecting and storing the data generated by thermal monitoring sensors. Depending on the sensor or data logger type, additional software and hardware may be needed to transform the collected data into a more easily utilized form for display or modeling purposes that can be used to support 316(a) studies. Table 4-3 contains more information regarding the capabilities and specification of various equipment types.[23]

Point Measurement

Temperature sensors are a common component of most environmental field monitoring equipment because they are generally small, cheap, and easy to calibrate and use. In addition to field equipment, thermistors can also be easily affixed to structures (piers, dams, flumes, etc.) or natural substrates (anchored or glued). These properties afford considerable flexibility in the placement and level of effort in retrieval of thermistors.

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[21] Here and below, the identification of specific firms or trademarks is for example only and does not constitute a requirement, endorsement or recommendation by EPA or any other government agencies.

[22] A thermistor is a temperature-sensitive resistor, whilst a thermocouple generates a voltage proportional to the temperature. While thermocouples can work at much higher temperatures, thermistors are more commonly used to measure ambient water conditions (typically -2 to 40°C).

[23] Note that Table 4-18 (and later, Table 4-19) contains specific brands and models of equipment; EPA presents this information as representative of the types of equipment available. The table is not intended to be an exhaustive list, not does it constitute an endorsement of any specific product.

Multi-parameter Field Instruments

Temperature sensors are frequently coupled with other water quality sensors in multi-parameter probes used for field monitoring. These handheld devices can be variously equipped to measure temperature, DO, conductivity, specific conductance, salinity, resistivity, total dissolved solids, pH, ammonium/ammonia, nitrate, and chloride.

There are several vendors for these multi-measurement instruments that offer a variety of handheld measurement devices and larger measurement systems. The cost of the handheld instruments increases with the number of probes attached, ranging from \$100-\$200[24] for a simple probe with temperature and pH sensors to approximately \$2,000 for a multi-parameter device. Note that the probes themselves will not operate without the companion handheld system, so the entire unit must be purchased. These systems usually require compatible data management software (often proprietary) which allows users to download and export data, configure instruments, conduct real-time studies, and view data graphically or in tabular form.

These instruments are effective for multi-purpose environmental monitoring because they can take many types of measurements and they are designed for rugged field work. However, these devices are not typically used for continuous temperature monitoring in support of Section 316(a) since data collection is limited to the time and location of the field technicians and more effective and less expensive systems are readily available.

Cabled Thermistors

Another means of water temperature monitoring uses thermistors attached to cables to allow measurement at a variety of depths, which is useful for 3-D plume delineation. Cabled thermistors can be mounted to docks or buoys, used in a temperature string arrays, or dragged behind boats for real-time monitoring events. When left in one place, these sensors may need several installations to provide overall spatial coverage. If the sensors are towed in the water for field monitoring, a pressure sensor is necessary to record the depth of the temperature measurement.

Thermistor cables up to 50 feet in length are relatively inexpensive (available from vendors such as Onset). These instruments require acquisition of a data logger and software program to use. Notably, the complete temperature sensor and data collection systems are one of the least expensive systems analyzed for this review. However, these sensors are not as durable as other temperature instruments and may last in water for only one year. Moreover, they may be subject to measurement drift when continuously exposed to water (Onset, 2015).

Distributed Temperature Sensing (DTS) Systems

Although DTS technology was created in the 1980s, its first usage for environmental temperature monitoring didn't occur until 2006 when the USGS presented field demonstrations of these systems. These demonstrations characterized estuary-aquifer and stream-aquifer interaction and for monitoring submarine ground-water discharge to coastal ecosystems. Since then, DTS systems have been used for

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[24] Any prices cited are for general comparison only and should be treated as approximate estimates.

thermal monitoring in estuarine and marine environments, groundwater environments, and dam monitoring and leak detection (Henderson et al., 2008, Slater et al., 2010; Ukil et al., 2012).

DTS systems are made up of fiber-optic cables connected to portable rack-mounted instruments that connect to computer hardware and collection software via Ethernet and USB (Universal Serial Bus) connections. Temperature is measured by light pulses sent along the fiber-optic cables and analyzed with either Raman or Brillouin backscatter. DTS systems typically measure at spatial resolutions of 1 m, temporal resolution of 1 minute, and thermal resolution of 0.1°C (Day-Lewis et al., 2006). New DTS technologies vary in their thermal resolution, with some commercial systems achieving resolution below 0.1°C. All systems appear to have a standard spatial resolution of 1 m. Spatial resolution of 1 m provides monitoring coverage for the length of the fiber-optic cable. Because of this fine-grained resolution, DTS systems can also be used to monitor stratification and circulation in lakes, large rivers, groundwater discharges and groundwater-surface water interactions. Thus, DTS systems are one type of thermal monitoring system that can be used to identify hyporheic flows or groundwater inputs to stream beds. The longest DTS cable system identified was 15 km long (SensorTran, 2015).

These systems provide major advantages over thermistors and data loggers because they are rugged and built to withstand rough water environments. With estimated useful lives of 30 years, DTS systems are good candidates for estuary and ocean monitoring. Depending on the sampling interval, sensor length and memory capacity of the system, data must be collected at frequencies of 2 to 15 years.

The biggest drawback with DTS systems is cost, with starting costs ranging from $30,000 to $100,000 (depending on factors such as cable length). Therefore, such systems are generally considered only for long-term monitoring programs and areas of high interest or economic value.

Temperature Arrays

Temperature arrays are systems that take measurements at multiple locations or depths in a waterbody. Arrays may be systems composed of multiple sensor strings or systems with associated data loggers that are set up to take measurements at multiple locations or depths in the waterbody.

Temperature string arrays are commonly used for lake monitoring projects where currents are much less than in riverine or estuarine environments. String arrays allow the user to sample at multiple depths, a feature particularly useful for sampling in stratified lakes that exhibit strong depth-temperature profiles. These systems can be put in place for continuous short-term or long-term monitoring. Depending on the system calibration and temperature drift over time, systems may need to be visited one to two times per year (Skinner & Lambert, 2006; Pyle et al., 2013). The strings are usually visited for the purpose of data extraction and equipment maintenance. Costs of these systems can be high, and the total cost depends on the number of sensors, sensor type, and the frequency of visits.

Temperature profilers, like temperature string arrays, provide better spatial coverage than single point measurements. Temperature profilers may be stationary vertical profilers or temperature sensors attached to monitoring buoys than can change location in a waterbody. These two profiler types provide different benefits and serve different monitoring purposes. The vertical profiler is typically used in reservoirs and drinking water sources for continuous long-term monitoring, whereas the buoy profiling system can be used for general monitoring of bays, harbors, estuaries or coastal waters. Users set up the monitoring frequency of these systems and the depth of the temperature measurements.

For some applications, sensor and profiling instruments may be connected to researchers or regulators via cellular telemetry, providing real-time measurements. These temperature sensors require maintenance every 6-8 weeks, and sensor and profiling systems typically last 6-8 years. These systems are expensive (about $50,000 for the full system), but these systems offer high-frequency, reliable temperature data.

Data Loggers

Temperature data loggers are essential for longer-term monitoring programs when users want to be able to deploy their sensors and return at a later data. Data loggers range considerably in physical size, memory, battery life, and application to certain waterbody types. These devices have local memories for storing measurements until the data is offloaded to a base station or sent directly to the computer via cables. Each manufacturer provides the base stations, cables, and software that connect to their devices.

Onset “HOBO” data loggers are commonly cited by researchers for use in thermal monitoring, particularly for stream networks. Their systems range from about $370 to $1,000 depending on the data logger type, with systems designed for use in saltwater environments costing more. Some models provide useful features such as being able to offload data in less than 30 seconds without removal from the water.

Other data logger brands reviewed included Gemini, Star Oddi, and ACR systems (see Table 4-3). These manufacturers produce sensors with similar measurement range, accuracy, and resolution, but differ in certain features that may be appropriate for specific environments or monitoring system. Some of these features include greater depth (e.g., systems can be submerged up to 36,000 feet); greater memory capacity (e.g., Star Oddi and ACR can store up to one million locally-stored readings) and longer battery life and field durability (e.g., up to 10 years of battery life use; MicroDAQ, 2015). Additional details are available in Table 4-3.

Table 4-3. Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Thermistors and Instruments								
Onset Air/Water/Soil Temperature (50' cable) Sensor - TMC50-HD	This temperature sensor can be used with HOBO U-Series, and it measures temperature in air, water, or soil.	Inexpensive. Sensor can be applied as a temperature string array or dragged by boat.	Sensors typically last only 1 year. Low spatial coverage. A pressure sensor may be needed addition for determining water depth during measuring.	-40° to 122°F	±0.45°F from 32° to 122°F	0.05° at 68°F	30 seconds is the typical response time	Up to 50 ft
Onset 12-Bit Temperature (17 m cable) Smart Sensor - S- TMB-M017	This temperature sensor has a stainless steel sensor tip and a cable that is designed to work with HOBO stations.	Sensor automatically communicates configuration information. Measurement averaging option.	Sensors typically last only 1 year. Low spatial coverage. If continually exposed to water for more than a year, it will eventually drift (<0.18°F per year).	-40° to 212°F	< ±0.36°F	< ±0.054°F	<1 minute response time	Up to 56 ft
YSI Pro2030 Dissolved Oxygen, Conductivity, Salinity Instrument	This handheld dissolved oxygen meter measures temperature, salinity, conductivity, specific conductance, TDS, and barometric pressure in addition to DO.	Multi-parameter measurement device. Designed for use in rugged field environments. User-replaceable sensors and cables.	Cost is greater than most temperature sensors because the instrument collects data on multiple parameters	23 to 131°F	±0.54°F	0.18°F	8 seconds	Cable options include 3, 12, 30, 60, or 90-ft cables

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
YSI Professional Plus (Pro Plus) Multiparameter Instrument	This handheld multiparameter meter measures temperature, dissolved oxygen, conductivity, specific conductance, salinity, resistivity, total dissolved solids (TDS), pH, ORP, pH/ORP combination, ammonium(ammonia), nitrate, and chloride.	Designed for demanding field work Instrument floats and is built to withstand 3-ft drops. Waterproof rated to IP-67 standards.	Cost is greater than most temperature sensors because the instrument collects data on multiple parameters.	23 to 158°F	±0.36°F	0.18°F	8 seconds	Cable options include 3, 12, 30, 60, or 90-ft cables
Distributed Temperature Sensing (DTS) Systems								
Lios Technology Temperature Monitoring System	Lios Technology manufactures fiber optic-DTS (FO-DTS) systems, which are optoelectronic devices that measure temperatures by means of optical fibers functioning as linear sensors.	Systems have the ability to characterize estuary-aquifer and stream-aquifer interaction. Lios makes the longest FO-DTS cables compared to other vendors considered (18 miles). Good for long term monitoring and rugged environments.	Systems are more expensive than typical temperature sensors.	Unknown	Unknown	<0.018°F	Seconds	<1 m spatial resolution

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
SensorNet Oryx DTS SR (3 mi range) / SensorNet Oryx DTS XR (0-9 km range)	SensorNet Oryx+ DTS systems are fiber- optic cable temperature measurement systems that are designed for harsh environments. The Oryx+ is an autonomous, low powered device that can be powered by solar or wind power.	High spatial coverage. Low measurement uncertainty Immune to shock/vibration and electromagnetic interference. Rugged systems that require very little power and can be powered by solar or wind energy. System can be left alone for long periods.	Systems are more expensive than typical temperature sensors	-40 to 149°F	Unknown	<0.018°F	10 second logging interval, 0.5 m sampling resolution.	1 m spatial resolution, 0.5 m sampling resolution
SensorTran ASTRA 5-10-15KM (3, 6, 9 mi range)	SensorTran's Astra single-laser DTS systems are fiber-optic cable systems that come with unlimited zoning/alarming capabilities and 3, 6, and 9 mi cable length systems.	High spatial coverage. Low measurement uncertainty. Systems available at 3 depth ranges. Systems available as either rack mounted and portable. Good for long term monitoring and rugged environments.	Systems are more expensive than typical temperature sensors	32 - 104°F	±1.8°F (5km and 10 km)±3.6°F (15km)	<0.18°F (5km and 10 km)<1°F (15 km)	10 second response time	1 m spatial resolution, 0.5 m sampling resolution

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

		Applicable Waterbodies										
Type	**Data Management System**	**Rivers**	**Streams**	**Lakes**	**Reservoir**	**Estuarine**	**Marine**	**GW**	**Durability**	**Cost**	**Related Article**	**Link to Product or Web Resource**
Thermistors and Instruments, cont.												
Onset Air/Water/Soil Temperature (50' cable) Sensor TMC50-HD	U12 ($249) and UX120-006M ($139) HOBO Data Loggers, which require HOB ware software and a USB interface cable ($99).	x	x	x	x				Sensor tip and cable immersion in fresh water for up to 1 year	Sensor: $50 Sensor and Software: $288-398		http://www.onsetcomp.com/products/sensors/tmc50-hd/
Onset 12-Bit Temperature (17 m cable) Smart Sensor - S-TMB-M017	U12 ($249) and UX120-006M ($139). Sensor parameters are stored inside the smart sensor, which automatically communicates configuration information to the station without any programming.	x	x	x	x				Sensor tip and cable immersion in fresh water for up to 1 year	Sensor: $120 Sensor and Software: $358-468		http://www.onsetcomp.com/products/sensors/s-tmb-m017
YSI Pro2030 Dissolved Oxygen, Conductivity, Salinity Instrument	Data Manager software ($190) is simple for downloading data, configuring instruments, and conducting real-time studies with Data Manager software. View data graphically or in tabular form and export data as needed to other programs.	x	x	x	x	x			3-year instrument; 2-year cable warranty	Sensor: $755 Sensor and Software: $945		https://www.ysi.com/pro2030

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoir	Estuarine	Marine	GW				
YSI Professional Plus (Pro Plus) Multiparameter Instrument	Data Manager is free with every YSI Professional Plus. This sensor has 5,000 data-set memory, password protection, backlit display and keypad, graphic display with detailed Help functionality, re-cal prompts, user defined fields, auto stable, Hold All Readings function, auto-buffer recognition, and flexible folders and site lists for logging data.	**x**	**x**	**x**	**x**	**x**			3-year instrument; 2-year cable warranty	Sensor and Software: $1,200		https://www.ysi.com/proplus
Distributed Temperature Sensing (DTS) Systems, cont.												
Lios Technology Temperature Monitoring System	No price available	**x**	**x**	**x**	**x**	**x**	**x**	**x**	No price available	No price available	Day-Lewis, F., and Lane, J., Jr. 2006. “Watershed-scale temperature monitoring of hydrologic processes [abs.]”. Hydro-geophysics Workshop, Vancouver, British Columbia, July 31-August 2, 2006, Proceedings, Society of Exploration Geophysics.	http://water.usgs.gov/ogw/bgas/fiber-optics/

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoir	Estuarine	Marine	GW				
SensorNet Oryx DTS SR (3 mi range) /SensorNet Oryx DTS XR (0-9 km range)	System can be configured and operated remotely through its Ethernet interface. Multiple communications ports, 32 Gb solid state storage an on- board PC.	x	x	x	x	x	x	x	Design life of 30 years	Approximately $40,000		http://www.sensornet.co.uk/technology/ distributed-temperature-sensing/oryx-dts-sensors
SensorTran ASTRA 5-10-15KM (3, 6, 9 mi range)	194 GB solid state hard drive. Requires software (Embedded OS (WES 7), DTS Commander™, AssetViewer™ or DTS FiberView™).	x	x	x	x	x	x	x	Over 15 years. Local data storage takes 2-15 years to fill depending on sampling regime	$35,000-$100,000 depending on system design		http://www.sensortran.com/stproducts_astra.php

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Temperature Array Systems								
Moored All-Season Vertical Temperature Arrays Application	Temperature monitoring arrays for this project consisted of a tandem instrument line and anchor line. Line sets consisted of anchors at the lake bottom, buoys near the lake surface, and intervening bridal lines.	The systems facilitate analysis of lake temperature trends. Possible to analyze lake stratification, isothermy, and climate change effects. Applicable to long-term monitoring in which systems must be checked every few months.	Spatial distribution may vary over time. No pressure sensor to determine precise water depth of measurements.	Maximum sustained temperature of 122°F in water	0.36°F over 32° to 122°F	0.036°F at 77°F	5 minutes in water. Daily logging intervals.	In study, maximum depth was 181 feet. Themistors were attached to the instrument lines at 15 or 30 ft intervals, depending on depth.
Smart Sensors for Continuous Monitoring of Temperature Stratification	The sensors enable low-powered radio or data loggers on buoys to command measurements and retrieve high-resolution temperature data. Multiple sensors at different vertical depths are deployed along a three-wire cable that provides power and allows data transfer at regular intervals.	Two-point calibration process facilitates in-situ calibration of sensor strings in stratified waterbodies provides a means to correct for long-term calibration drift	If the two-point calibration system is not used correctly, accuracy will be lower due to low-cost sensors used. Complex data processing (requires the use of the method of finite differences to calculate temperature).	23°F to 122°F	0.018°F from 32°F to 122°F when using the two-point calibration procedure	±0.005◦F with intersensor matching of±0.01◦F	Unknown	In study, maximum depth was 52 feet (similar to the length of the Onset thermistor cable sensors)
YSI System Buoy Products	YSI sensor (EXO1 Multiparameter Sonde) attached to buoy that can be deployed from a small boat or from shore. Available as a lightweight spar buoy, a harbor buoy, bay buoy, coastal buoy, or pontoon platform.	Rapid, single person deployment. Routine servicing is simple and fast. Measurements can be seen in real-time. Systems can be used for short or long term monitoring.	High cost	23°F to 122°F	±0.018°F	0.0018°F	<1 second	Maximum depth is 82 ft

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Temperature Array Systems								
YSI 6950 Fixed Vertical Profiler	YSI sensor (EXO1 Multiparameter Sonde) is used with fixed vertical profiling system that can be programmed to move up and down the water column at regular intervals. The system wirelessly transmits the data from to the base. Also available as a buoy and pontoon platform profiler.	Systems can be mounted on a dam, pier, piling, or other stationary locations. Measurements can be seen in real-time. Wireless or direct connection data transmission available.	High cost. Shorter warranty compared to the YSI handheld instruments	23°F to 122°F	±0.018°F temperature accuracy±0.3 3 ft spatial accuracy	0.0018°F	<1 second	Cable options include 164 and 328 ft

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoirs	Estuarine	Marine	GW				
Temperature Array Systems, cont.												
Moored All-Season Vertical Temperature Arrays Application	Study used Onset® HOBO® U22 Water Temp Pro V2 Data Loggers. Data was transferred from the sensors to a database in the office. The database used was a custom-made Microsoft Access database to manage the data and provide graphing and export functions.			x	x				System can last as long as the data logger battery life. System required twice yearly visits for the purpose of data extraction, maintenance, and deployment and retrieval.	Total project cost was about $40,000 over 2 years for 10 lakes	Pyle, B. et al. 2013. "Moored All-Season Vertical Temperature Arrays in Lakes on Kodiak, Togiak, and Alaska Peninsula/Becharof National Wildlife Refuges." *U.S. Fish and Wildlife Service.*	https://westernalaskalcc.org/projects/SitePages/WA2011_04.aspx
Smart Sensors for Continuous Monitoring of Temperature Stratification	Thermistors connect to an analog-to-digital converter (ADC) to digitize the measurement and a microcontroller responsible for computations, control and communications. Algorithms are used to convert the raw measurement into a calibrated temperature, then software algorithms are used to correct for the temperature coefficients of the sensor's electronics. The system also needs a component for updating and storing individual sensor calibration coefficients and a means of			x	x	x			System has the potential to last as long as the life of thermistor cables. Study continuously operated the sensor strings for over 12 months.	Thermistors cost less than $1, but must be water-proofed after purchase (no cost estimate). Thermistors are attached to cables and the SDI-12 interface bus to connect sensors to radios or data loggers (no cost estimate).	Skinner, A. and M. Lambert. 2006. "Using Smart Sensors for Continuous Monitoring of Temperature Stratification in Large Water Bodies>" *IEEE Sensors Journal* 6(6): 1473-1480.	dx.doi.org/10.1109/JSEN.2006.881373

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoirs	Estuarine	Marine	GW				
	communicating with data loggers or computers.											
YSI System Buoy Products	Buoys are deployed with wet-chemistry nutrient and metal analyzers, current meters, water quality monitors, GPS, atmospheric sensors, wave sensors, hydrocarbon sensors, and more. Users can add satellite, radio, or cellular telemetry to the buoy to send data to a custom visual display to get real-time data. Compatible with YSI EXO measurement sensor or 3rd party device.			x	x	x	x		Systems last many years(?). Wind speed resistance depends on buoy system.	Buoy: $10,600 (Harbor) -$44,000 (Coastal) Data Logger: $4,500-6,500 YSI Sensor (EXO2): $8,655 Mooring: $980-2,250 Shipping: $317-1,300 Full System: $25,052-62,705		http://www.ysisystems.com/products
YSI 6950 Fixed Vertical Profiler	Compatible with YSI EXO measurement sensor or 3rd party device. Profilers come with Profile Wizard software for set-up and deployment.	x	x	x	x	x	x		1-year warranty on main profiler unit, but systems can be used for many years.	Fixed Profiler: $29,035 Telemetry system: $3,200 YSI Sensor (EXO2): $8,855 YSI Level Sensor: $3,000 Shipping and Installation: $5,300 Full System: $49,930		https://www.ysi.com/6950FixedVerticalProfiler

Table 4-3. (Continued) Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Data Loggers								
HOBO Data Loggers								
Tidbit v2 Water Temperature Data Logger (UTBI-001)	This data logger is Onset's smallest data logger at 3x4 cm. It is 12-bit resolution and designed for outdoor and underwater use.	Small data logger that can be mounted easily and withstand water environments. Data can be transmitted to the HOBO coupler in less than 30 seconds while in the field. Data offload possible when wet.	Non-replaceable battery.	Maximum sustained temperature of 86°F in water	± 0.38°F over 32° to 122°F	0.04°F at 77°F	5 minutes in water	Up to 1,000 ft
Water Temperature Pro v2 Data Logger (U22-001)	This 12-bit resolution data logger is designed with a durable streamlined case for extended deployment in fresh or salt water.	Factory-replaceable battery. Data can be transmitted to the HOBO coupler in less than 30 seconds while in the field. Data offload possible when wet.	Shorter battery life compared to other data logger brands.	Maximum sustained temperature 122°F in water	± 0.38°F over 32° to 122°F	0.04°F at 77°F	5 minutes in water. Logging interval is 1 second to 18 hours	Up to 400 ft
HOBO 30-Foot Depth Water Level Data Logger (U20-001- 01)	This data logger measures temperature, water level, and pressure in shallow wells, streams, lakes, wetlands and tidal areas.	Data logger can also log water depth and absolute pressure. No-vent-tube design allows for easy deployment. Durable ceramic pressure sensor for reliable performance. Calibration certificate included.	Shorter battery life compared to other data logger brands. Greater cost than typical temperature data loggers because the instrument also collects data on water depth and pressure.	-4° to 122°F	± 0.79° over 32° to 122°F	0.18° at 68°F	5 minutes in water	Up to 100 ft

Table 4-3. (Continued) Types and Specifications of Various Thermal Monitoring Equipment

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Other Data Loggers								
Gemini TinyTag Aquatic 2 (TG 4	This data logger is submersible with a high visibility bright yellow case and an attachment point for secure positioning. The sensor was designed for long term immersion.	Able to measure at large depths. Highly visible. User-replaceable battery.		-40°F to 158°F	± 0.9°F over 32° to 122°F	<0.018°F	<20 minutes in moving water, Logging interval is 1 second to 10 days.	Up to 1,640 feet
Star-Oddi DST Centi-T Temperature Data Recorder	This data logger is a 12-bit resolution, small (1.5 cm x 4.6 cm), submersible, biocompatible data logger for measuring and recording temperature.	Housed in alumina, which is an implantable, biocompatible Ceramic Material. Includes 25 years of data retention and a long (7 year) battery life.	Small size may result in misplacement of data logger if not properly mounted.	30°F to 104°F	±0.18°F	0.058°F	20 seconds response time. Logging interval is seconds to hours.	Up to 11,480 ft
Star-Oddi Starmon Temperature Data Recorder	This data logger is a 12-bit resolution underwater temperature data logging device made for harsh underwater environments.	Largest memory options available. Longest battery life for data loggers (10 years). Able to withstand large depths and harsh environments.		28°F to 104°F	±0.045°F	0.0018°F	3 minutes and 1 minute for plastic and titanium housing. Logging interval is 1 Second to 90 Hour.	Up to 1,312 and 36,089 ft for plastic and titanium housing, respectively.
ACR Systems Nautilus85 High Temperature Waterproof Data Logger	This data logger is durable with aluminum or stainless steel housing options. It is designed for hostile and underwater environments.	Able to withstand high pressures (2000 psi) and hostile water environments. Longest battery life for data loggers (10 years).	8-bit resolution compared to 12-bit resolution of HOBO and Star-Oddi data loggers.	-40 to 185°F	0.36°F over -32°F to 158°F	Unknown	Logging interval is 8 Seconds to 34 Minutes.	Up to 4,000 ft

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoirs	Estuarine	Marine	GW				
Data Loggers, cont.												
HOBO Data Loggers,												
Tidbit v2 Water Temperature Data Logger (UTBI-001)	42,000 readings memory. Connects to software at HOBO Base Station via a coupler. Require Base Station or Waterproof Shuttle ($124-249), Coupler ($11-20), and HOBOware Pro Software and USB cable ($99)	x	x	x	x				5 years with 1 minute or greater logging interval	Data logger: $133 Full System: $367-492		http://www.onsetcomp.com/products/data-loggers/utbi-001
Water Temperature Pro v2 Data Logger (U22-001)	42,000 readings memory. Connects to software at HOBO Base Station via a coupler. Require Base Station or Waterproof Shuttle ($124-249), Coupler ($11-20), and HOBOware Pro Software and USB cable ($99)	x	x	x	x	x	x		6 years with 1 minute or greater logging interval. Factory-replaceable battery.	Data logger: $129 Full System: $363-488		http://www.onsetcomp.com/products/data-loggers/u22-001
HOBO 30-Foot Depth Water Level Data Logger (U20-001- 01)	21,700 readings memory. Connects to software at HOBO Base Station via a coupler.	x	x	x	x	x	x		5 years with 1 minute or greater logging interval	Freshwater data logger: $495 (stainless steel) Saltwater data logger: $595 (titanium) Full system: $729-954		http://www.onsetcomp.com/products/data-loggers/u20-001-01

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

		Applicable Waterbodies										
Type	**Data Management System**	**Rivers**	**Streams**	**Lakes**	**Reservoirs**	**Estuarine**	**Marine**	**GW**	**Durability**	**Cost**	**Related Article**	**Link to Product or Web Resource**
Other Data Loggers, cont.												
Gemini TinyTag Aquatic 2 (TG 4	32,000 measurements memory. Requires SWCD-0040: Tinytag Explorer software ($80) and an ACS-3030: USB Inductive Pad ($60).								Built to last for many years. Battery needs replacing every 1 year, but battery is user-replaceable	Data logger: $175 Full system: $315		http://www.geminidataloggers.com/data-loggers/tinytag-aquatic2
Star-Oddi DST Centi-T Temperature Data Recorder	174,000 or 523,800 readings with extended memory option. Requires a Communication Box ($399) and PC Software from Star-Oddi (SEASTAR or MERCURY, $271).	x	x	x	x				7 year battery life	Data loggers: $259 (174K readings) or $296 (523K readings) Full system: $929-966		https://www.microdaq.com/star-oddi-centi-temperature-data-recorder.php
Star-Oddi Starmon Temperature Data Recorder	350,000, 787,500 or 1,048,500 readings with extended memory option. Requires communication cable ($139) and PC software (SEASTAR,$271).	x	x	x	x	x	x		10 year battery life, user-replaceable	Plastic Data Loggers: $425, $471 or $487 depending on memory. Titanium Data Loggers: $795, $841 or $857 depending on memory. Full system: $835-1,267		https://www.microdaq.com/star-oddi-starmon-temperature-data-recorder.php

Table 4-3 (Continued). Types and Specifications of Various Thermal Monitoring Equipment

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoirs	Estuarine	Marine	GW				
ACR Systems Nautilus85 High Temperature Waterproof Data Logger	244,800 readings with data compression. Requires TrendReader Software from Nautilus ($139) and cable kit.	x	x	x	x	x	x		Data loggers has 4- year warranty. 10-year battery life.	Data loggers: $289 (aluminum) or$369 (stainless steel) Full System: $428-508		https://www.microdaq.com/acr-systems-nautilus85-waterproof-data-logger.php

4.2.3 Remote Sensing

Thermal remote sensing involves the acquisition, processing and interpretation of data acquired primarily from the TIR region of the electromagnetic spectrum (typically 3-5 and 8-14 µm). Measurements of water temperature are made with sensors that detect thermal radiation emitted from the upper 0.1 mm of the water surface (Torgersen et al., 2001). Since temperature is measured at the surface layer of the water it may not be representative of the temperature in water column, which usually is of more interest biologically (Handcock et al., 2012).

The major advantage of thermal remote sensing is the ability to rapidly obtain thermal data for large geographic areas. Remote sensing can quickly display current thermal conditions, establish thermal gradients in large or lengthy waterbodies, or allow comparison of mainstem and tributaries. It can provide better detail of spatial heterogeneity of thermal conditions than is possible with a network of fixed sensors. Remote sensing can also alleviate legal or logistical problems of gaining access to private lands or geographically remote areas and provide a spatial content for evaluating relationships between water quality and surrounding land use (Torgersen et al., 2001).

Thermal remote sensing methods (Table 4-4) can be functionally grouped based on the nature and height of the sensor deployment and can be categorized as handheld (ground) systems, airborne systems and satellite-based sensing systems. An overview of the advantages and disadvantages of each of these systems as compared to conventional thermal monitoring is provided in Handcock et al. (2012) and summarized in Table 4-5.

Handheld TIR sensing

This category includes highly portable hand-held instruments capable of high-resolution thermal imaging at a local scale. These cameras have been adapted for a wide range of diverse uses including energy audits, water leak detection, power line maintenance, firefighting, and hunting.

Thermal cameras can be used to image streams, lakes, and adjacent structures (e.g., banks, bars, seeps) to quickly locate and characterize thermal anomalies in real time at a scale of centimeters to tens of meters (USGS, 2015). They are very useful for groundwater-surface water interaction studies where variations in temperature can be used to trace changes in the receiving water’s heat signature such as during periods of groundwater discharge into a stream. On the other hand, handheld TIR imagery can be limited by the difficulty in locating sites with a clear line-of-sight at an elevation sufficient to resolve significant stretches of stream or river channel.

Highly localized data produced by TIR sensors can be used to determine the extent and sustainability of habitat quality and thermal refugia for heat-sensitive wildlife. For example, USGS researchers used a thermal-imaging camera to support brook trout restoration activities through thermal characterization of groundwater inflows to trout streams, delineation of extent of stream areas that brook trout seek for thermoregulation, and rapid assessment of thermal mixing zones (USGS, 2013).

Airborne Thermal Sensing

Forward looking infrared (FLIR) cameras are typically mounted on airplanes, helicopters, or drones and use a thermographic camera that senses IR emitted from a heat source to create a display that can be assembled digitally for video output. If TIR data are combined with flight navigation data (i.e., GPS coordinates), large scale aerial TIR maps can be developed using geographic information systems that facilitate detailed analysis and interpretation.

Handcock et al. (2012) indicated that the most extensive use of airborne TIR remote sensing recently has been by natural resource management agencies seeking to calibrate spatially explicit river temperature models for entire watersheds. Agencies can use this information to evaluate TIR images of rivers over time to assess changes in the thermal landscape associated with habitat degradation or to evaluate the effectiveness of floodplain restoration.

One example of FLIR use is a thermal survey of the Scott and Shasta River sub-basins in California. This survey was done to support the characterization of salmonid rearing habitat in the rivers and tributaries as a function of river flow, springs, channel hydraulics (width, depth, and velocity), and riparian shade (Watershed Sciences, 2004). Thermal data were collected with TIR (8-12µ) and visible-band cameras attached to a gyro-stabilized mount on the underside of a helicopter which was flown longitudinally along the stream channel at constant height. TIR images were recorded directly from the sensor to an on-board computer in a format in which each pixel contained a measured radiance value. The individual images were referenced with time and position data provided by a GPS.

Satellite-based TIR sensing

Remote sensing by satellite is a well-established practice, particularly in oceanography where daily observations of regional and global sea-surface temperature (SST) are made (e.g., Kilpatrick et al., 2001; Parkinson, 2003). The advantages of satellite-based TIR imaging over airborne TIR include: greater area coverage, variable pixel sizes, number of bands, a wider field of view and greater sensor sensitivities (Handcock et al., 2012). If available and the pixel size is appropriate, TIR satellite images can be an attractive source of broad-scale data due to their low cost, capability for regional coverage, and the potential for repeat monitoring.

Thermal data are collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) located on the National Aeronautics and Space Administration’s (NASA’s) Terra and Aqua spacecraft (NASA, 2015). Temperature maps may be generated using the MODIS direct broadcast SST software, distributed as part of the International MODIS/AIRS Processing Package (IMAPP). Examples of this application for freshwater include the Great Lakes (NOAA, 2015) and the Great Salt Lake (Grim et al., 2013). While these are large waterbodies, Grim et al. (2013) provides techniques that could be applied to any other inland body of water large enough to be resolved by MODIS, as long as sufficient *in situ* water temperature observations were available for calibration.

Satellite imagery has been used in coastal applications appropriate for Section 316(a) studies. Chen et al. (2003) depicted thermal pollution from the cooling water discharge of a nuclear power plant using Landsat TM data. This method could be applied to other thermal mixing studies, depending on the scale of the thermal plume.

Table 4-4. Types of Remote Sensing Systems for Thermal Monitoring.

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Remote Sensing Systems								
Forward Looking Infrared Radiometry (FLIR), or Handheld Thermal Infrared Cameras	Forward looking infrared (FLIR) cameras use a thermographic camera that senses infrared radiation.	Lower cost than airborne remote sensing. Monitors groundwater-surface water interactions. Measures the effect of water flow on temperature profiles. Measures the effect of vegetation indices and shade over stream channels on temperature.	This technology is typically manufactured for purposes other than environmental monitoring. In riverine monitoring, near-bank objects may result in an increase in observed temperature.	-4°F to 482°F	Unknown	<0.18°F	Immediate	In-situ remote monitoring of streams
Thermal Infrared Remote Sensing	Thermal infrared sensing detects infrared radiation from surfaces. Sensors can be attached to satellites, airplanes, or on the ground to deploy and validate in situ.	High spatial coverage. Systems can quantify spatial patterns in rivers, streams, and floodplains, at multiple spatial scales throughout entire watersheds.	Time-consuming. Costly. Obtaining images can be difficult. Complex raw data processing required to produce calibrated temperature maps. In riverine monitoring, near-bank objects may result in an increase in observed temperature.	Full temperature range over water and land temperatures	Unknown	NA	Sampling windows are dependent on temperature changes. Range of 2-4 hours is best	Option of a fine-scale resolution (0.2-1 km) for groundwater springs and cold- water seeps or large- scale resolution (1-150 km) for entire river sections and floodplains

Table 4-4 (Continued). Types of Remote Sensing Systems for Thermal Monitoring.

Type	Product Information	Advantages	Disadvantages	Measurement Range	Accuracy	Resolution	Temporal Response	Spatial Scale
Moderate Resolution Imaging Spectroradiometer Land- Surface Temperature (MODIS- LST)	The Moderate-resolution Imaging Spectroradiometer (MODIS) is a scientific instrument (radiometer) launched by NASA in 2002 on board the Aqua satellite platform (a second series is on the Terra platform) to study global dynamics of the Earth's atmosphere, land and oceans.	Extremely accurate and reliable. Data for many years is free to access. Web-based tools are available that can be used to access a variety of datasets.	Sources of error in measurement include sun glint, water vapor absorption in the atmosphere, trace gas absorption, and episodic variations in aerosol absorption (e.g., volcanic eruptions, terragenous dust blown out to sea)	Full temperature range over ice, ocean, and land temperatures	<0.18°F	NA	Datasets available in 30 min to 1 day intervals	Sea surface temperature available at 1-km and 4.6 km, 36 km, and 1° (Level3)
Advanced Very High Resolution Radiometer (AVHRR)	Broad-band, six channel scanner, sensing in the visible, near-infrared, and thermal infrared portions of the electromagnetic spectrum. The latest sensor instrument version is AVHRR/3, with 6 channels, first carried on NOAA-15 launched in May 1998.	Global coverage. Reliability. Continuity of access. Wide application of multiple decades of data collected by NOAA.	NOAA has seen challenges with this technology as a result of conflicting desires by users for greater support for their own scientific disciplines with more advanced sensors and more sophisticated customer support	-157 to 122°F	Unknown	NA	Coverage from 1978-present	1.1-km by 4.4-km spatial resolution
Multi-point Measurement Control System Application	Multi-point monitoring system that uses digital temperature sensors with 1-wire bus interface to transfer data. The system uses multiple temperature sensors, several functional module components, and a computer.	One-wire digital temperature sensor (they used DDS18B20) is very cheap (~$4). Measurements are precise and real-time. Able to be used for power plants.	System setup may be complicated. Connections to computer are available, but article does not specify what software program was used, if any.	0 -85°C (32 - 185°F)	0.1 °C	0.0625 °C	Real-time display of measurements	System can be hooked up to a measuring rod lifter to take temperature measurements at different depths.

Table 4-4 (Continued). Types of Remote Sensing Systems for Thermal Monitoring

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoir	Estuarine	Marine	GW				
Remote Sensing Systems, cont.												
Forward Looking Infrared Radiometry (FLIR), or Handheld Thermal Infrared Cameras	Application software is needed to process the data. Like other remote sensing technologies, data processing can be complex and difficult to calibrate.	x	x					x	Unknown	$500-20,000 depending on camera	Larson, L. et al. 2002. "Perspectives on water flow and the interpretation of FLIR images." *Journal of Range Management* 55: 106-111.	http://www.omega.com/pptst/OSXL-T620.html
Thermal Infrared Remote Sensing	Interpretation of TIR image data to determine water temperature can be complex and expensive, and requires trained technical expertise. Care must be taken to interpret TIR images within their terrestrial and aquatic context. Radiometric correction is necessary to accurately retrieve quantitative temperatures from TIR data accurately.	x	x	x	x	x	x		Permanent sensors can last for decades at a time	Expensive if not using sensors that are already in use	Handcock, R. et al. 2012. "Thermal Infrared Remote Sensing of Water Temperature in Riverine Landscapes." Fluvial Remote Sensing for Science and Management, 1st ed. Edited by Patrice E. Carbonneau and Herve Piegay. Published by John Wiley.	http://faculty.washington.edu/cet6/pub/Handcock_etal_2012.pdf

Table 4-4 (Continued). Types of Remote Sensing Systems for Thermal Monitoring

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoir	Estuarine	Marine	GW				
Moderate Resolution Imaging Spectroradiometer Land- Surface Temperature (MODIS- LST)	MODIS data are transferred to ground stations in White Sands, New Mexico, via the Tracking and Data Relay Satellite System (TDRSS). The data are then sent to the EOS Data and Operations System (EDOS) at the Goddard Space Flight Center. Ocean color products are produced by the Ocean Color Data Processing System (OCDPS) and distributed to the science and applications community.	x	x	x	x	x	x		Datasets cover up to 20 years	Data is made freely available by NOAA		http://modis.gsfc.nasa.gov/data/dataprod/mod28.php
Advanced Very High Resolution Radiometer (AVHRR)	NOAA processes data from AVHRR. Data are acquired in three formats: 1) High Resolution Picture Transmission (HRPT) data (full resolution image data transmitted to a ground station as they are collected), 2) Local Area Coverage data (full resolution data that are recorded on an onboard tape for subsequent transmission during a station overpass), and 3) Global Area Coverage data (derived from a sample averaging of the full resolution AVHRR data).	x	x	x	x	x	x		2-year design lifetime for processing, but system has been in place for multiple decades	NOAA extracts no fees for establishing and operating an HRPT direct-readout ground station. Ground stations can be constructed for under$100,000 and possibly as low as several hundred dollars (over 200 already in operation).	Hastings, David A., and William J. Emery, 1992. The Advanced Very High Resolution Radiometer (AVHRR): A Brief Reference Guide. Photogrammetric Engineering and Remote Sensing, vol. 58, No. 8, August 1992, pp. 1183-1188.	https://www.ngdc.noaa.gov/ecosys/cdroms/AVHRR97_d1/avhrr3.htm

Table 4-4 (Continued). Types of Remote Sensing Systems for Thermal Monitoring

Type	Data Management System	Applicable Waterbodies							Durability	Cost	Related Article	Link to Product or Web Resource
		Rivers	Streams	Lakes	Reservoir	Estuarine	Marine	GW				
Multi-point Measurement Control System Application	Temperature data acquisition converter is integrated with the multi-bus module LTM-8663, isolated communication converter LTM-8520 and switching power supply module.								Unknown	Sensor, $4; LTM-8663 system, ; LTM-8520 system, $82	Xinsheng, W., et al. 2010. "Design and application of multi-point water temperature measurement and control system for thermal discharge model." *IEEE Computer Society 2010 International Conference on Digital Manufacturing &Automation.*	

Table 4-5. Comparison of Conventional vs. TIR Thermal Monitoring (Table 5.1 from Handcock et al. 2012)

Table 5.1 Comparison of conventional measurements and TIR remote sensing for regional assessment of water temperature in rivers and streams.

	a)	Conventional Measurements	TIR Remote Sensing
Data acquisition	Advantages	• Measurements can be made at any point in the water column. • Limited technical expertise is needed to gather data. • Data can be obtained under most weather conditions including fog and cloud cover. • Continuous measurements are possible using data loggers. • Costs of collecting data can be low, depending on the number of instruments that must be deployed.	• An alternative to collecting validation data is to use existing networks of in-stream data loggers. **Satellite** • Capability for regional coverage, repeat monitoring with systematic image characteristics, and low cost. • Data can be gathered across multiple scales from local (e.g., upwelling ground-water) to regional (entire floodplains). **Airborne** • Can measure TIR images at fine pixel sizes suitable for narrower streams and rivers. **Ground** • Instruments are easy to deploy and validate *in situ*; requires physical access to the stream.
	Disadvantages	• Sparse sampling of T_k in space. • Gives limited information about the spatial distribution of water temperature. Data loggers can be destroyed or removed by vandalism or floods. • Data are collected only at point locations. Do not provide a view of the entire thermal landscape of the river. • Temperature gauges are typically located in larger streams and rivers. • Calibration of thermometers is still necessary. • To collect spatially extensive measurements, it is necessary to deploy many personnel.	• Obtaining TIR images can be costly and complex, and temporally limited. • Care must be taken in interpretation of TIR data under off-nadir observation angles and with variable surface roughness (i.e., diffuse versus specular reflections). **Satellite** • TIR images may not be available due to cloud cover, limited duty cycle of platforms used to collect data (satellite orbits, or availability of aircraft). **Airborne** • Generally covers narrow swath widths (i.e., small areas) compared to satellite data. • Acquisition costs can be high, especially if multiple overlapping scan lines are needed to create a mosaic. **Ground** • Can only view the water from specific locations along the stream. • Observation angles need to be chosen carefully to reduce the effects of reflections from objects along the river bank.

	b)	Conventional Measurements	TIR Remote Sensing
Data Processing	Advantages	• Standard data storage and processing techniques can be used (knowledge of the hydrological system is still necessary).	• For applications in which having a non-absolute temperature is useful, non-radiometrically corrected TIR images can be used to assess relative spatial patterns within a single image. • Validation is not required for applications that only need relative temperatures.
	Disadvantages		• Interpretation of TIR image data to determine water temperature can be complex and expensive, and requires trained technical expertise. • Care must be taken to interpret TIR images within their terrestrial and aquatic context. • Radiometric correction is necessary to accurately retrieve quantitative temperatures from TIR data accurately, but this can be time consuming and expensive. • For data acquired from aircraft, changes in the stability of the aircraft as it flies can require complex and costly post-processing of images.
	c)	**Conventional Measurements**	**TIR Remote Sensing**
Applications	Advantages	• T_k can be measured directly, which is both of interest biologically and applicable to management objectives.	• Repeatable, spatially extensive, and systematic measurements. • Can quantify spatial patterns of water temperature in streams, rivers, and floodplains at scales ranging from less than 1 m to over 100 km. • Can view the entire thermal landscape of the river, not just point locations. • Consistent data source for entire floodplains and can be used to calibrate stream temperature models. • TIR image data and concurrent visible and NIT images (when available) can be used to assess both the water surface and adjacent riparian areas. • Repeat flights can be used to assess habitat degradation.
	Disadvantages	• Difficult to collect spatially extensive data to use to calibrate stream temperature models for entire watersheds.	• T_k is measured at the surface layer of the water and may not be representative of T_K in the water column, which is of interest biologically. • Trade-off between pixel-size (i.e. to identify spatial patterns and reduce mixing with bank materials) and the cost of conducting broad-scale surveys.

4.2.4 Examples of Temperature Monitoring Programs

Temperature monitoring systems for Section 316(a) demonstrations or thermal mixing zone studies are designed to provide sufficient temporal and spatial data about water temperatures, often in three dimensions: to develop, calibrate, and verify thermal mixing models used to predict potential impacts of thermal plumes under a variety of different operating scenarios. Thermal monitoring systems are highly site-specific and are tailored to the facility discharge flow and plume, as well as adjacent (near-field) and regional (far-field) environments and the thermally-sensitive receptors they contain. Wagner et al. (2006) provides a summary of some of the factors need to be considered in selecting both the type and location of monitoring equipment in designing a monitoring network (Table 4-6).

Table 4-6. Factors for Consideration in the Placement and Installation of Continuous Water-Quality Monitoring Systems (from Wagner et al., 2006)

Site Characteristics
• Potential for water-quality measurements at the site to be representative of the location being monitored. • Degree of cross-section variation and vertical stratification. • A channel configuration that may pose unique constraints. • Range of stream stage (from low flow to flood) that can be expected. • Water velocity. • Presence of turbulence that will affect water quality measurements. • Conditions that may enhance the rate of fouling, such as excessive fine sediments, algae, or invertebrates. • Range of values for water quality field parameters. • Need for protection from high water debris damage. • Need for protection from vandalism.
Monitor Installation
• Type of state or local permits required before installation can begin. • Safety hazards relevant to monitor construction and installation. • Optimal type and design of installation. • Consideration of unique difficulties or costs of installation.
Logistics (maintenance requirements)
• Accessibility of site, including parking or boat access. • Safe and adequate space in which to perform maintenance. • Presence of conditions that increase the frequency of servicing intervals needed to meet data-quality objectives. • For stream sites, proximity to an adequate location for making cross-section measurements. • Accessibility and safety of the site during extreme events (for example, floods, or high winds). • Availability of electrical power or telephone service. • Need for real-time reporting.

For additional general information on thermal monitoring planning and design refer to Handcock et al. (2012); EPA (2013); or Wagner et al. (2006).

Monitoring systems for Section 316(a) demonstration range from fairly simple upstream-downstream comparison of unidirectional flows to complex systems required to capture information in irregular, multi-channel environments subject to tidal flushing and other anthropogenic influences. As indicated in the earlier sections, the tools employed for these systems are highly varied and evolving, the development of relatively inexpensive, automated thermistors and data loggers or TIR imaging provide the means for more extensive and cost-effective monitoring. Not all thermal monitoring to support Section 316(a) demonstrations or thermal mixing zone studies will require this level of sophistication, and there is no “one-size-fits-all” design.

The following examples of thermal monitoring design give some indication of the potential range of complexity and effort that may be required to satisfy thermal modeling data needs. These monitoring design examples and facilities are listed in order of complexity and include:

- Section 316(a) Re-Verification Study Plan for A.M. Williams Steam Electric Generating Station (GeoSyntec, 2009) (in-situ, river);
- Bay Shore Thermal Zone Mixing Study (LMS, 2003) (in-situ, bay);
- E.F. Barrett Hydrothermal Surveys and Modeling (NA & ASA, 2009) (in-situ, tidal and wetland); and
- Use of TIR imagery for Crooked River, Oregon (Handcock et al., 2012) (remote, small river).

A.M. Williams Station, Goose Creek, SC

The Section 316(a) demonstration for the A.M. Williams Station near Goose Creek, SC required temperature monitoring for a relatively short stretch of the tidally influenced Cooper River (GeoSyntec 2009). This stretch of the Cooper River is somewhat isolated from local anthropogenic activities and hydrologic inputs other than the station's discharge, simplifying the study design and implementation.

Water temperature monitoring was conducted at ten transects, placed perpendicular to water flow, above and below the Williams Station discharge canal, to delineate the lateral and vertical extent of the thermal plume (Figure 4-1). From previous studies it was known that the heat of the plume dissipates rapidly, so transects were clustered near the discharge canal and were spaced farther apart as distance from the canal increased. Plume mapping was performed during two seasonal events: once in the spring during the period of high biological productivity, and again in the summer during the high temperature-low flow critical conditions period. During each of the two sampling events (spring and summer), the thermal plume was laterally and vertically delineated four times during a 12-hour period: during ebb tide, low slack tide, flood tide, and high slack tide.

Water temperature was measured using a portable water quality analyzer across the full width of the river from the surface to below the depth of the thermal plume. Measurements were recorded at depths of 1, 2, and 4 m at six points spaced equidistant along each transect. Geographic coordinates of transect locations and measurement points were recorded in the field. Ambient water temperature was determined by measuring a number of surface temperatures at increasing distances from the discharge canal until it was determined that there was no thermal gradient. Ambient temperature was checked for consistency (±1°C) with water temperature recorded at a nearby USGS gauging station. Further details are provided in GeoSyntec (2009).

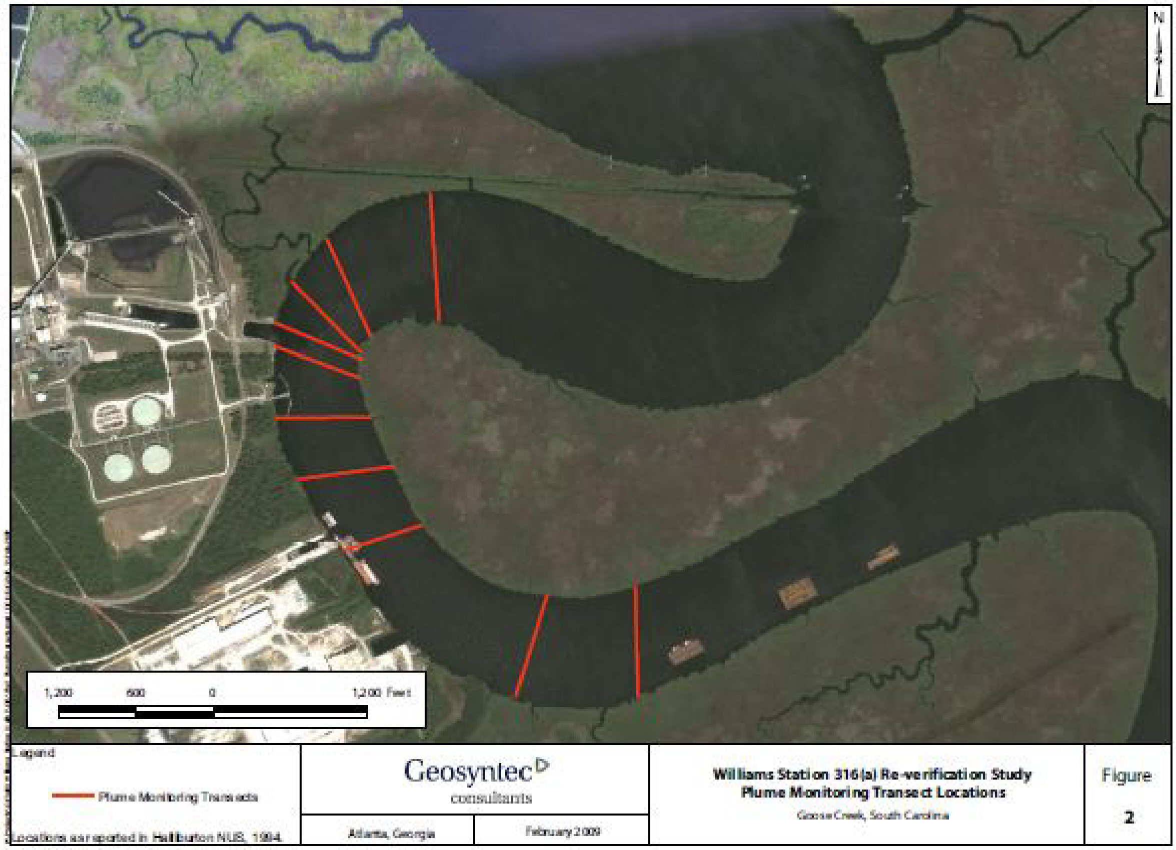

Figure 4-1. Transect Locations for Thermal Monitoring of A.M. Williams Station (from Geosyntec, 2009).

Bay Shore Station, Oregon OH

A thermal mixing zone study, conducted for the Bay Shore Station, Oregon, OH, provides an example of thermal monitoring conducted in a simple coastal environment (LMS 2003). Bay Shore is located on a peninsula between the mouth of the Maumee River and the shore of Maumee Bay. The facility draws cooling water from the Maumee River and discharges heated effluent into the Bay, a shallow embayment contiguous with the open waters of Lake Erie. Temperature modeling consisted of five mobile surveys (cruises) and deployment of 21 fixed water temperature monitoring stations (moored buoys) within Maumee Bay (Figure 4-2). Data obtained were used to support the thermal mixing model (i.e., CORMIX).

Mobile surveys were scheduled at approximately three-week intervals during the summer (June-September) to collect thermal data representing a wide a range of meteorological and limnological conditions. Water temperature and current velocities were recorded simultaneously at one-second intervals along planned track lines. The boat periodically stopped (3-7 times) during the surveys to profile vertical temperatures, particularly in areas expected to be within the thermal plume, or test for thermal stratification. Boat position was determined by a differential global positioning system (DGPS) unit.

Locations of the 21 fixed monitoring stations were determined from preliminary CORMIX modeling results and a reconnaissance survey. At each location, temperature logger was deployed with the sensor just below the surface (19 locations) or measuring both top and bottom temperatures (2 locations). Temperatures were logged in 6-minute intervals. The entire set of sensors was replaced during each mobile survey so that no individual instrument was submersed longer than the duration between surveys.

The water temperature data was combined with the plant operating data, and meteorological data to model the thermal plume, with the ultimate goal of generalizing the observed conditions to a wider range of potential conditions and extrapolating the spatial extent of a reasonable “worst-case” plume based on relevant historical conditions. Further details are provided in LMS (2003).

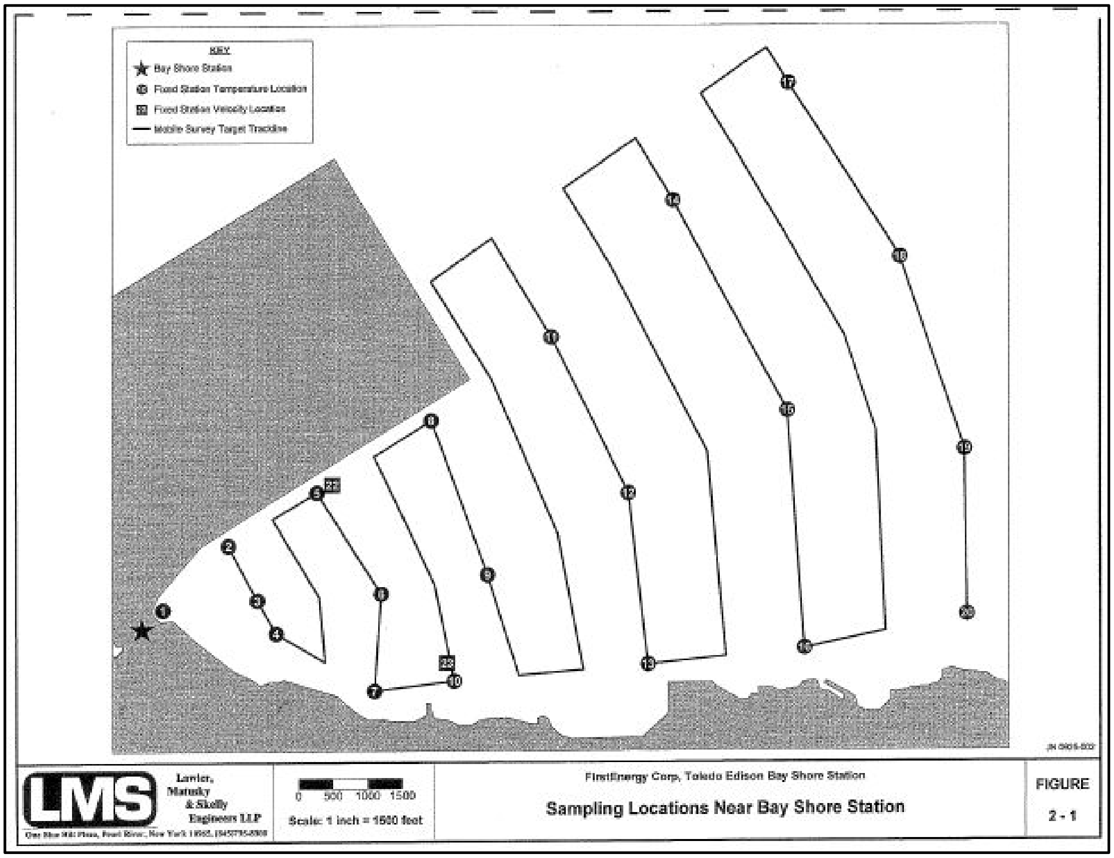

Figure 4-2. Sampling Locations and Survey Track lines near Bay Shore Station (from LMS, 2003).

E.F. Barrett Station, Hempstead Bay, NY

The E.F. Barrett Station required an extensive network of thermal monitoring to support thermal plume modeling in a complex estuarine area (NA & ASA, 2009). Thermal effluent from Barrett (situated at location 4 on Figure 4-3) discharges to an irregular channel system bordering significant tidal wetland areas. Field monitoring was designed to characterize the facility’s thermal discharge plume and its receiving-water environment under prevailing summer conditions. For this field effort, the following types of thermal data were collected:

- Shipboard surveys of water temperature along horizontal cruise tracks;
- Vertical temperature profiling at various locations within the facility’s plume; and
- Continuous temperature measurements at various mooring locations.

The shipboard surface temperature sampling program was designed to characterize and delineate the magnitude and areal extent of the facility’s thermal plume under slack-before-flood and slack-before-ebb tidal conditions. This was accomplished by measuring surface water temperatures along multiple horizontal transects, so as to include surface water temperatures exceeding 1.5°F above ambient. A DGPS unit with sub-meter resolution was used to map sample locations. Figure 4-3 shows the cruise track from one of the summer surveys.

Vertical profiles of temperature and salinity were collected by conductivity-temperature-depth recorders at select locations along the shipboard survey to characterize the vertical structure of the thermal plume and the receiving-water environment. The survey was timed to obtain as much coverage as possible within a 2-hour window around the slack-water intervals. Vertical profile sampling was performed simultaneously with the shipboard cruise activities using a separate boat and crew.

For background information, continuous monitoring was conducted using a set of 12 moored arrays of temperature sensors/data loggers (±0.1°C) that automatically logged time and water temperatures every 5 minutes. Conductivity (or salinity) and temperature measurements were recorded at three depths (near-bottom, at mid-depth, and near-surface). For spatial coverage, the continuous temperature monitoring units were moored at several locations in Hempstead Bay (not shown) including one control site that was established to provide representative ambient conditions.

The information from the field program was combined to characterize temperature distributions in three dimensions for use in estimating thermal exposures of biota for the biothermal assessment. Further details are provided in NA & ASA (2009) and related permit documents.

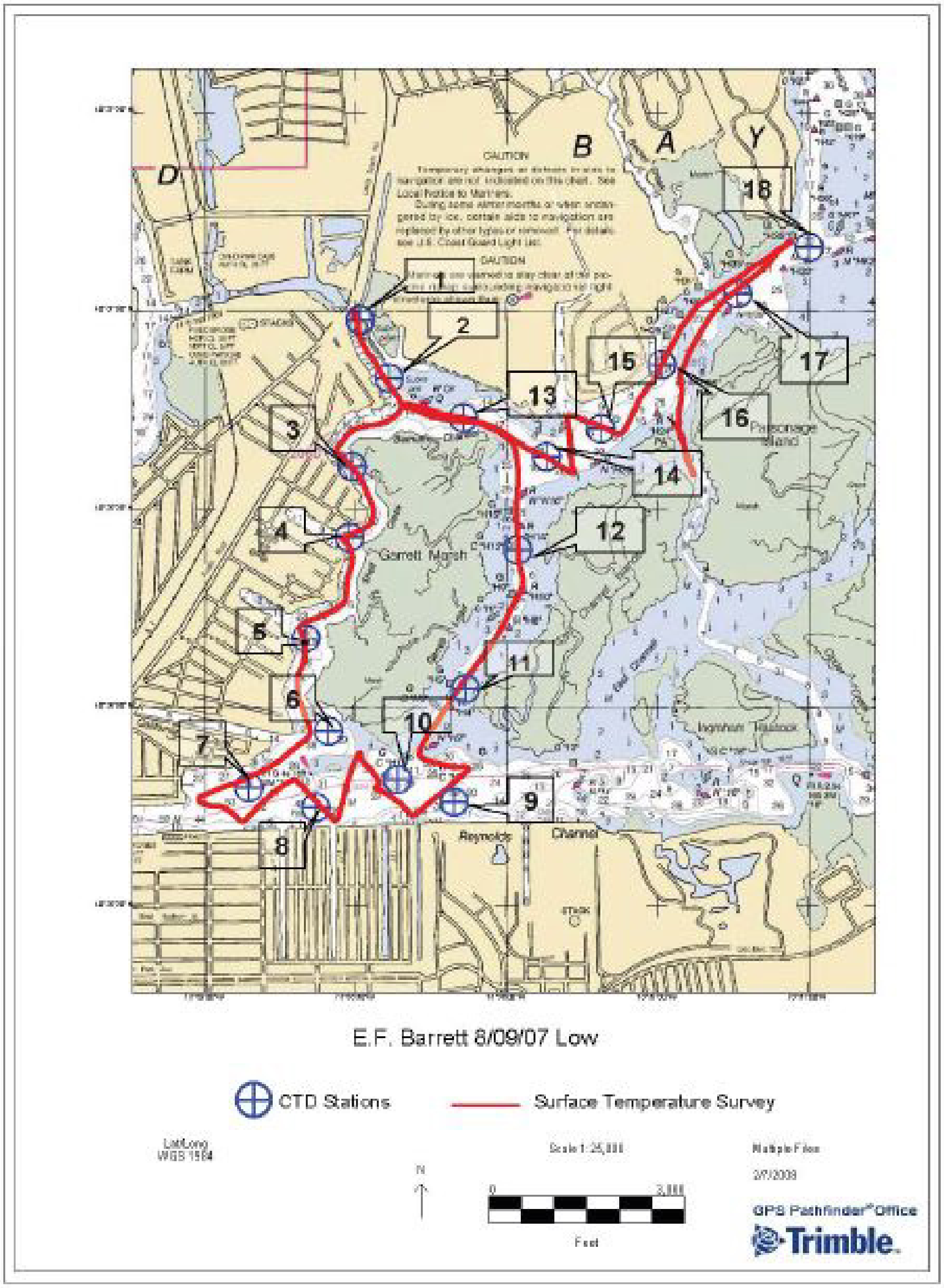

Figure 4-3. Shipboard Survey Track and Locations of Vertical Temperature Profile Sites Near E.F. Barrett Station (from NA & ASA, 2009).

Small River Environment (TIR Imagery)

Section 316(a) demonstrations are typically conducted for large power generation stations that draw water and/or discharge to relatively large bodies of waters such as large rivers, lakes and reservoirs, and coastal areas. The demand for a large volume of cooling water, as well as easy transport of bulk fuel material (e.g., rail transportation, barges, etc.) has precluded siting power plants on small rivers or streams. However, future power needs may be met by construction of smaller, natural-gas powered generation plants located in more interior or arid environments. In these locations, even a small volume of thermal discharge may constitute a relatively high percentage of the receiving water flow, or in some cases, virtually the entire waterbody flow.

In these cases, characterization of thermal characteristics in rivers subject to high variations in flow or subject to seasonal drought may be more easily accomplished by airborne TIR imagery, particularly if the study area is remote, not easily accessed, lacks power to run equipment or has a highly irregular (braided) channel morphology. For small rivers, inputs of cooler groundwater or the presence of hyporheic flow during summer months may be hydrologically important and critical in providing thermal refugia for sensitive species. These types of flows are not easily captured by the use and scale of conventional temperature monitoring systems. Figure 4-4 compares natural color (a) and TIR (b) images of the Crooked River in Oregon. The TIR image clearly shows a cold-water seep that may act as a thermal refuge (Handcock et al., 2012).

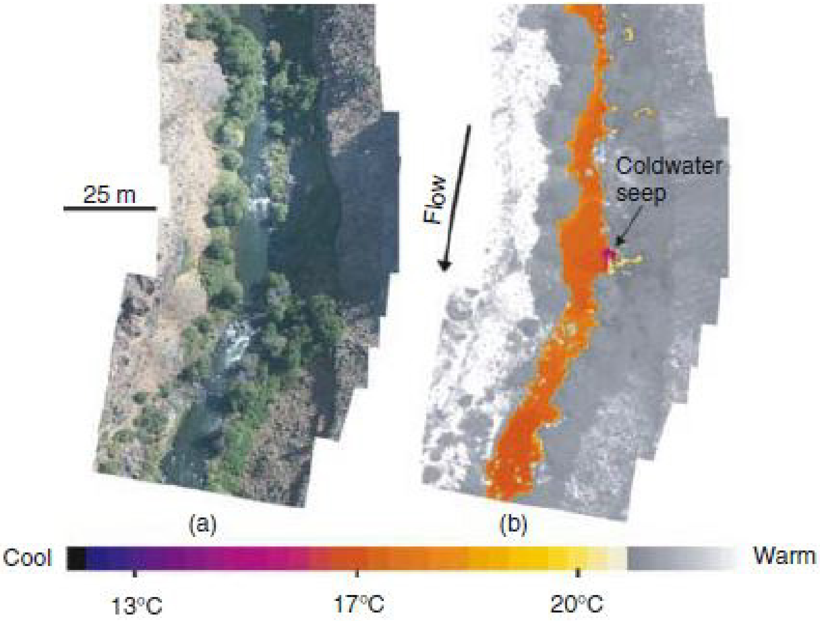

Figure 4-4. Comparison of Natural Color and TIR Imagery; Crooked River, OR (from Handcock et al., 2012).

4.2.5 Section 4.2 References

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4.3 Evaluating Temperature Mitigation Technologies

EPA reviewed the range and efficiency of current temperature mitigation technologies or techniques for reducing the water temperature of discharges and thermal impacts on receiving waters. EPA provided an overview of a representative range of thermal mitigation methods, including those more appropriate for smaller dischargers (e.g., publicly-owned treatment plants (POTWs)), moderate-to-large industrial dischargers, and major power plants. These thermal mitigation methods are presented in an annotated format (Table 4-7).

From these methods, EPA selected seven mitigation techniques for further evaluation including: riparian shading, flow augmentation, hybrid cooling systems, spray cooling, helper cooling towers, heat recovery, and diffusers. These techniques were selected to highlight their utility to dischargers of all sizes, but may be of particular use to smaller dischargers.

4.3.1 Introduction

Thermal effluent from point source discharges (e.g., POTWs, industries, power generation plants, and other facilities) can cause or contribute to exceedances of applicable temperature WQS, or can cause stress to sensitive components of the aquatic ecosystem. Thermal impacts due to facility discharges have been shown to result in alterations of ambient temperature, shifts in local flow, shifts in migratory patterns, displacement or disruption of seasonal flow or thermocline regimes, degradation of aquatic habitat quality and other effects (Flieschli and Hayat 2014, also see Section 4.3.4). Thermal pollution concerns are typically addressed under the CWA Section 402 and Section 316(a) regulations, which govern requests for variance and set requirements for thermal mixing zone modeling and/or demonstration studies.

Historically, CWA Section 316(a) investigations or thermal mixing zone modeling have been mostly conducted by power-generation facilities or industries which generate large volumes of heated effluent (e.g., pulp and paper mills, major industrial plants). However, EPA expects that smaller dischargers may increasingly need to address thermal provisions as part their NPDES permits.

There are several reasons for this expected increase in the number of small dischargers with permit conditions directly regulating thermal impacts on receiving waters. The hydrologic impacts of climate change present a greater probability of increasing drought frequency and magnitude, resulting in increased water temperature, reduced mixing volume, and shallower discharge depths. EPA regions have documented increases in thermal exceedances and water quality violations and this trend is likely to worsen as climate change effects could reduce the volume of river water available for operations and the river’s capacity to absorb waste heat (White 2013; Fricko et al. 2016; Stillwell and Saunders 2016). Increases in intake water temperatures can also reduce operation and power production efficiency. The number of smaller dischargers exceeding thermal criteria is likely to increase as the ability of the receiving water to buffer heat inputs decline and more stringent thermal criteria are set for the protection of temperature-sensitive species and habitats (Henning 2014). These small dischargers may not be able to utilize traditional thermal mitigation methods, such as closed cycle cooling, due to economic and consumptive use considerations.

In addition, the source and methods of power generation are shifting – with greater reliance on natural gas, solar power, and wind-generated power and decreasing numbers of fossil-fuel or nuclear powered plants. Accordingly, future power plants will be much less dependent on being in close proximity to rivers, lakes or estuaries to provide large volumes of cooling water or for bulk transport of fuel. Development of natural gas plants in arid sections of the western U.S. will lead to the siting of facilities in regions where consumptive use of water for cooling water purposes is costly or infeasible (Miara et al. 2013).

These trends have motivated research and development of a wide range of thermal mitigation methods or technologies to dissipate heat more efficiently from the effluent and provide greater ability and flexibility in meeting thermal criteria.

4.3.2 Data Sources

EPA investigated thermal mitigation methods applicable to dischargers of varying type and scale. Several documents were useful as references for methods of thermal mitigation over a range of discharge flows. These articles, reports, and documents included are listed below:

- Bushart, S. 2014. Advanced Cooling Technologies for Water Savings at Coal-Fired Power Plants. Cornerstone: 2:52-57;
- Clean Water Services (CWS), February 2005. Revised Temperature Management Plan for the Rock Creek and Durham Wastewater Treatment Facilities;
- Leffler, et al. 2012. Alternative Heat Rejection Models and Associated Impacts. Cooling Technologies Research Center (CTRC) Research Publications. Paper 159.;
- Maulbetsch, J. and J. Stallings. 2012. Evaluating the Economics of Alternative Cooling Technologies Power Engineering 116(11):1-9;
- OR DEQ, July 2000. Oregon Temperature Management Plan – Guidance Manual, Chapter 5.0 – “POTW BMPs”;
- Skillings Connolly, Inc. 2007. “Methods to Reduce or Avoid Thermal Impacts to Surface Water. A manual for small municipal wastewater treatment plants.” Prepared for Washington Department of Ecology. Water Quality Program. Ecology Publication #07-10-088; and
- SPX Cooling Technologies (SPX). 2009. Cooling Tower Fundamentals. 2nd edition. J. C. Hensley (Ed.). Overland Park, KS.

In addition, EPA obtained additional data and information from available scientific literature or dedicated searches of internet materials (see Section 4.3.5).

4.3.3 Thermal Mitigation Methods

Efforts to mitigate the negative impacts of elevated water temperatures and water consumption and to protect aquatic ecosystems have given rise to many strategies and engineered technologies meant to cool heated discharge water. Table 4-7 provides a summary of over 20 methods identified from the literature review. This list is thorough but not comprehensive. EPA noted that, for many methods, there are numerous variations possible for a given engineering design or approach, particularly for those methods that are still rapidly advancing (Bushart 2014; Engineers Australia 2015).

Table 4-7 includes a brief general introduction, necessary elements, and advantages and disadvantages for each method. EPA classified the type and size of facilities that would be most likely to use these thermal mitigation methods, based on the design of the applications and the amount of effluent volume and heat load expected to be dissipated. These categories include: small dischargers and POTWs (defined as less than 1.0 million gallons per day (MGD)), intermediate, moderately large dischargers and POTWs (defined as in the 1.0 – 10.0 MGD range), and large dischargers and power plants (defined as greater than 10.0 MGD). Table 4-7 also identifies whether there are existing examples of the method. In some cases, interesting or innovative thermal mitigation methods have been proposed but have not been implemented to date and/or scaled up for use at moderate-to large power plants and remain largely hypothetical (Leffler et al. 2012).

For any discharger, thermal mitigation costs are site-specific. Each facility site differs as to the availability of land (e.g., land application, piping distance), construction needs (e.g., cooling ponds, constructed wetlands), availability of adjacent waters (e.g., diversion, blending or discharge relocation), local climate (e.g., greenhouse heating, hybrid cooling) or other factors. In addition, the size of the facility and the volume of effluent to be treated will vary, resulting in uncertainty regarding cost and economic feasibility.

Instead, a more qualitative assessment of cost was developed. Relative costs of implementation were estimated based on available information and current examples of the proposed method. The relative range of costs were classified as either 0 (no cost) or ranged from “$” (expected low cost) to “$$$$” (significant costs such as plant redesign). Due to a lack of information or real-life examples, the costs of implementation of proposed designs or hypothetical methods were simply classified as “NA” (not available).

From the methods listed in Table 4-7, EPA selected seven for further investigation. Section 4.3.4 provides a detailed discussion of the selected methods, as well as information on how each method was selected for the detailed review.

Table 4-7. Methods of Thermal Mitigation

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Influent or In-Plant Modifications (Pre-Discharge)								
Pre-treatment of heat loads	Pretreatment reduces influent temperature and heat loads from industrial and commercial waste inputs prior to entry to facility (EPA standard influent limit is 40˚C).	External wastewater customers constitute a significant source of heated water to the facility.	Targets and addresses the greatest heat loads. The financial burden for pre-treatment is on input sources not the discharger.	Need to establish and enforce local pretreatment standards; additional staff and time needed to regulate.	Small industrial dischargers or POTWs.	Many cities have pre-treatment ordinances or regulations that prescribe effluent water quality and physical properties.	None, paid by industrial users	EPA (1986), EPA (1987)
Clarifier covers	Provide shade over the clarifiers or other treatment processes to reduce solar radiation prior to discharge.	Facilities where solar input increases the effluent temperature significantly prior to discharge.	The reduction of solar input, pollutants, or debris to the wastewater; also, exclusion of rain and snow, and reduction of algal growth.	Cost, winter heat loss, potential increase of delta-T between discharge and receiving water.	Small POTWs.	No current example of clarifier covers use for thermal mitigation.	NA	Geomembrane Technologies, Inc. (GTI) or Ultraflote (as cited in Skillings Connolly 2007)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Disinfection alternatives	Enclose the chlorine contact chamber or UV system to reduce the amount of solar heating of the wastewater.	Most applicable if the existing disinfection system is already scheduled for replacement for another reason.	Reduction in solar input.	Initial purchase costs and operating costs. This method uncertain to deliver significant results.	Small POTWs.	No current example of enclosed disinfection systems for thermal mitigation.	NA	Metcalf and Eddy (2003)
Process or treatment modifications	Modification of internal process or methods to reduce facility heat output.	Heat-producing processes or production steps capable of being eliminated or mitigated.	Reduced power and compliance costs.	Potential for significant costs; may not be feasible to alter processes to reduce heat significantly.	Moderate to large industrial discharges.	Many examples of retrofits or modifications for pulp and paper mills.	$$-$$$	Technical Association of the Pulp and Paper Industry (TAPPI) (2005)
Water quality trading	Water quality trading programs could include temperature as a pollutant and establish a credit system.	Policy development and program oversight, willing partners or a market that can support trading.	Allows dischargers to find the most efficient solution. Can be flexible with the means of trades (e.g., riparian shading versus installing a cooling pond). May be existing trading programs in place for a given watershed.	May not be enough credits available. Takes time to develop and implement a program.	Small industrial dischargers or POTWs.	Used in a small number of locations, such as Tualatin River (OR) and Ashland (OR).	$$-$$$	CWS (2020)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Heat Recovery								
Heat recovery	Heated effluent can be reused for any number of other processes within the permitted facility or transferred to a neighboring facility for heating purposes.	Infrastructure to reroute the effluent to a new location or process. Another process or entity that needs water. Heat recovery equipment.	Reduces the temperature in heated effluent. Provides energy savings to the permitted facility or neighboring facility.	Piping and pumping to reroute water may be extensive/costly. Second entity needs to be in close proximity. May be consumptive use.	Manufacturers, industrial processes, POTWs, cogeneration/steam production, residential.	Many different types of manufacturing facilities use a heated effluent stream to heat another process stream. Heated effluent streams can also be used for commercial and residential heating.	$-$$$	Mikkonen et al. (2013), Muller et al. (2013)
Ocean Thermal Energy Conversion	Heated effluent can be reused to heat a working fluid in a power cycle that uses cooler seawater as a heat sink, thus cooling the effluent while generating electricity.	Pumping system to supply cooler deep ocean water, power generation equipment.	Reduces the temperature in heated effluent. Generates power that can be used or sold. Blends effluent with cooler sea water.	Limited temperature reduction in heated effluent due to the sea water being blended with the effluent prior to discharge. Relatively low power output. High capital costs for deep ocean pumping equipment	Large facilities located in close proximity to deep ocean water.	Very few examples are in use.	$$$	Kim et al. (2010)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Thermal Effluent Modification								
Seasonal storage	Storage of effluent during the critical temperature period (e.g., late summer) until receiving water temperature and/or flow conditions allow resumption of discharge without WQS exceedance or harm to aquatic habitat.	Sufficient land to construct a reservoir of adequate volume to store/detain effluent over the critical period.	Simplicity of design, and very low operation and maintenance costs; creation of recreational opportunities or ecological habitat with associated benefits.	Potentially high capital costs for: land, basin construction, impounding structure along with design and permitting costs; flow reduction problematic if receiving water is already flow impaired.	Wide range from small facilities, municipal POTWs, industrial plants and power plants.	Storage and seasonal release is practiced at many facilities including power plants.	$-$$$ (depends on land cost)	Skillings Connolly (2007)
Flow augmentation/ Effluent blending	Mixing effluent with cooler surface or groundwater; allowing sufficient holding time for temperature equilibration prior to discharge.	Have access to adequate source of surface water that could be released on demand for this purpose or groundwater aquifer that has capacity to accept injected water.	Use of effluent blending is easy to apply on a seasonal or as needed basis; it can also help to augment instream flow. Blending through groundwater recharge can support water reuse policy goals.	The availability and cost of blending water, or securing water rights for this use. New piping may be necessary.	Small facilities or municipal POTWs.	Flow augmentation is used in the Tualatin River Basin (NW OR) to offset thermal inputs of 2 POTWs.	$-$$ (depends on water resource)	CWS (2005), CWS (2014), Leffler et al. (2012)
Thermal Discharge Relocation or Modification								
Discharge location	Relocation of the discharge structure (to different stretch of the receiving water or to another	Feasible if large waterbody or other mainstem	Reduces thermal impact to the existing receiving water; good for	Costs for pipe and discharge structure; loss of flow from intake source, altered	Small facilities or municipal WWTP.	Proposed as retrofit design for smaller facility. Uncommon	$$-$$$	OR DEQ (2000)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
	waterbody) to avoid thermal impacts to receiving water that is already thermally impaired.	channels are located within reasonable proximity to the discharger.	seasonal use; possible flow augmentation of instream flows.	receiving water hydrology; relocated effluent impact on alternate receiving water; and permitting issues.		for existing facilities due to the cost and logistics.		
Modification of discharge structure/ Diffuser	Modify discharge structure by addition of multiple ports or improved diffuser valve design for more rapid and complete mixing.	Usually involves retrofitting a facility that currently uses a single point discharge or an existing outfall pipe with a small number of ports.	Multi-port diffuser systems direct the effluent in several locations simultaneously; particularly useful in areas that are tidally influenced or have variable water levels. Can promote rapid mixing of entire effluent volume, not only temperature.	Requires retrofitting or replacement of the outfall pipe and regular maintenance and purging of lines; thermal modeling may be required for design and permitting.	Small facilities, POTWs, industrial plants, and power plants.	Common retrofit to enhance rapid mixing and reduce zone of initial dilution.	$-$$	Tideflex (as cited in Skillings Connolly 2007)
Land application and Indirect discharges								
Land application (agricultural application)	Uses sprinklers or irrigation system to deliver effluent to an area where crops or trees are being cultivated.	Land application feasible where irrigated crops and permeable soils are	Shifting effluent discharge from surface water to land application when receiving water	Piping costs, non-permeable soil types, topography, and existing land use may be constraints; not	Small-to-moderate sized facilities or municipal POTWs.	City of Walla Walla (WA), (12 MGD) POTW, diverts effluent flow to two irrigation	$-$$	Ohio State University (1997), TAPPI (2005), WA Dept of Ecology (2005)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
		located within close proximity to the discharge facility.	temperatures are most critical.	applicable in all climates.		districts during the summer.		
Infiltration and exfiltration methods	Thermal discharge is directed into an infiltration trench or exfiltration gallery which delivers effluent into the subsurface; sometimes below a confining layer.	Flat topography, remote from buildings, slopes, highways, wells, or infrastructure. With exfiltration, some surface land uses may be feasible.	Potential use on a seasonal basis for limited discharges; could provide flow augmentation.	Only feasible for small discharges; more commonly used for stormwater management.	Small dischargers or POTWs.	Reports of use of exfiltration galleries for POTW (0.035 MGD) in VT.	\$-\$\$	Skillings Connolly (2007), Vermont RUS (undated)
Constructed wetlands	Constructed wetlands would be used as the initial receiving water to reduce thermal impact through evapotranspiration, shading of the wetlands to reduce solar input, and long detention time.	Assumes that sufficient land, wetland soils, and a source of water is available for constructing or restoring wetlands or natural wetlands that could be augmented are available.	Theoretical models estimate that 2-5°F of cooling may be achievable; other benefits include effluent polishing prior to release, and creation of an attractive public amenity.	Initial costs, design and permitting, land requirement, establishment of viable wetland, uncertainty of thermal load reduction, and creation of a potential vector hazard.	Small-to-moderate sized facilities or municipal POTWs.	Used by industrial facilities and POTWs for treatment of a variety of pollutants, including temperature (see Ashland OR POTW)	\$\$-\$\$\$	Skillings Connolly (2007), EPA (2015b), Darling (2018)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Algal bioreactor	An open-water algae bioreactor pond transfers heat from discharge water to a shallow pond with a layer of algae growing on the surface.	Algae bioreactor is a circular pond that is opaque and well-mixed.	Supports growth of thermophilic cyanobacteria (BGA) all year round; dissipates heat and provide potential biofuel.	Cost of building and operating large pond and harvesting BGA. Not readily used or effective biofuel.	Small dischargers or POTWs.	No example of algal bioreactor use for thermal mitigation were identified.	NA	Chisti and Yan (2011), Chinese et al (2005), WA Dept of Ecology (2021), Leffler et al. (2012), Demirbas (2011)
Greenhouse heating	A greenhouse heated in the wintertime by the waste heat from a power plant to grow agricultural products year-round.	Condenser discharge water pumped through pipes in the soil transfers heat through conduction.	Utilizes waste heat to produce food and other bioproducts.	Installation and maintenance cost; may be light-limited; may not be useful in southern climates.	Small dischargers or POTWs.	No current example of greenhouse use for thermal mitigation.	NA	Leffler et al. (2012)
Direct Cooling of the Effluent								
Riparian shading	Shading provided by planting riparian trees or shrubs to reduce direct solar radiation heating and thermal input to receiving water.	Small width waterbody which will be effectively shaded by trees planted along its banks. Riparian land availability.	Relatively cheap to implement and based on natural cooling system; positive public acceptance in urban areas; tree and shrub overhangs create fish habitat or thermal refugia.	Not practical for larger rivers due to limited shore-based shading; trees need to be established and replenished, lag time to reach useful tree size; introduction of organic leaf litter and debris.	Small dischargers or POTWs.	Used as watershed BMP in the Tualatin River Basin (OR) to offset thermal inputs of 2 POTWs.	\$-\$\$	CWS (2005), CWS (2013), Niemi et al. (2008), University of Minnesota (2010)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Cooling ponds	A cooling pond is one or a set of reservoir(s) designed to receive thermal discharge and reduce heat, through evaporative and radiative heat loss, prior to discharge or can be closed system (i.e., no discharge).	Sufficient land to construct one or more reservoirs of adequate volume to temporarily detain effluent.	Simplicity of design, and minimal power costs; creation of recreational opportunities or ecological habitat with associated benefits.	Capital cost for: land, basin construction, and impounding structure; more effective cooling in climates or seasons with a large differential between the heated water and wet bulb temperature.	Moderate-to-large industrial dischargers and power plants.	One of the most common thermal mitigation methods used for large power plants.	$$-$$$	Ryan et al. (1974), TAPPI (2005)
Cooling canals	A shallow-water canal system can be used to reduce heat, through evaporative and radiative heat loss before re-entry to the condenser or discharge to a lake.	Land to construct canal system where it can be easily integrated as part of the plant flow path and provide enough detention for meaningful heat loss.	Simplicity of design, and low operating and maintenance costs.	Capital cost for canals; if used as sole thermal mitigation tool, it could require a network of interconnected canals; would be an expensive retrofit option.	Small facilities, municipal POTWs, industrial dischargers, and power plants.	Canals are often used for cooling and conveyance of flow; a design proposal for a power plant (FL) using only cooling canals was identified.	$$-$$$	Leffler et al. (2012)
Spray cooling	Nozzles spray heated discharge water into the ambient air; heat loss from the sprays and pond surface occur through evaporation of	Land to install ponds, power for pumping, and maintenance costs; effective in climates (or seasons)	Spraying cools and aerates, producing a well-oxygenated effluent at lower temperature, for discharge;	Spray cooling may require a large number of nozzles and power; potential drift away from the pond; water loss reduces return flow to	Small facilities, municipal POTWs, industrial dischargers, and power plants.	Examples of large facilities using spraying for thermal mitigation include Dresden NPS and Celgar Pulp Company	$-$$$	Codell (1986), Leffler et al. (2012), Shell and Wendt (undated)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
	water and convective heat transfer.	when there a minimum 10°C difference between effluent and ambient wet bulb temperature in order to have effective evaporative cooling.	space required for spray cooling is much less than for a static cooling pond.	the receiving water with potential for adverse impacts to fish habitat during drought or low-flow conditions.		bleached kraft pulp mill (BC, Canada); it is also used in many small municipal WTTPs.		
Cooling Towers and Mechanical Devices								
Closed cycle cooling tower (wet)	Water goes from the condenser to cooling towers where heat is dissipated through evaporation; the rest of the cooling water is then recirculated through the condensers.	Sufficient land area; can be incorporated into original plant design or retrofitted to replace once through cooling water (OTCW) systems.	Compared with OTCW, closed-cycle cooling significantly reduces water withdrawal and related aquatic impacts; cooling towers are easy to operate and maintain.	More water is lost through evaporation in closed cycle cooling systems than in OTCW; so consumptive use of water is greater; may impact low-flow situations.	Moderate-to-large industrial dischargers and power plants.	Widely practiced for thermal mitigation in large power plants, including retrofit scenarios.	$$$-$$$$	Maulbetsch and Stallings (2012), SPX (2009), EPA (2014)
Closed cycle cooling tower (dry)	Dry cooling systems are similar to wet closed-cycle systems, except that the evaporative cooling tower is replaced with dry cooling	Generally, these are incorporated into original plant design, but could be retrofit to replace OTCW	This method uses virtually no water and thus offers a new plant greater siting flexibility (independent	Effectiveness of dry cooling depends on the ambient air temperature and humidity; plant efficiency is lower for	Moderate-to-large industrial dischargers and power plants.	Widely practiced for thermal mitigation in large power plants.	$$$-$$$$	Bushart (2014), Maulbetsch and Stallings (2012), SPX (2009)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
	towers where ambient air is used to cool the circulating water.	or wet towers where water is scarce.	of waterbodies) and effectively eliminates most aquatic impacts.	plants using dry cooling systems, especially in hot, arid climates.				
Helper cooling towers	A helper tower is a cooling tower that is sized to reduce the thermal effluent to an acceptable level, often on a seasonal basis.	These can be designed or retrofitted into existing plants for environmental compliance with thermal limits.	Operating cost and flexibility. Under certain circumstances of heat load and ambient water temperature, the thermal effluent may be cool enough, and the helper tower can be shut down.	Construction costs and integration into existing plant; must be correctly sized to reduce thermal load under wide range of environmental conditions.	Moderate-to-large industrial dischargers and power plants.	Increasingly practiced for thermal mitigation in large power plants where cooling needs are moderate or only seasonal in nature.	$$$-$$$$	Bushart (2014), Mallory (2012), SPX (2009)
Hybrid wet-dry cooling tower	Hybrid cooling systems combine dry cooling and wet cooling to reduce water use relative to wet systems.	Hybrids cooling systems are commonly used when water is available but not in the quantities necessary to support a 100% wet cooled system.	Hybrid systems have the potential for more than 50% water savings compared to wet cooling towers while improving warm weather performance.	Generally, more expensive that recirculated wet cooling towers alone, and significant water may still be needed during the summer; has all of the operation and maintenance issues of both cooling systems.	Moderate-to-large industrial dischargers and power plants.	Newer form of cooling tower technology, so not commonly used. Newer, smaller generating units can increase net power output during period of high ambient temperature.	$-$$$	Bushart (2014), Engineers Australia (2015), SPX (2009)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
Solar updraft tower (i.e., solar chimney)	With a modified solar updraft tower, heat is dissipated from the power plant via a heat exchanger located at the base of the tower; a heat exchanger absorbs heat from power plant as it preheats the air going into the solar collector.	A solar updraft tower has a tall tower, a large solar collector (or other energy source) at the base, and a gas turbine where the collector and tower meet.	Uses excess heat from power plant to provide rising thermal air flow to turbine.	Cost, reliability; a solar tower is usually designed to run on solar energy (not dependent on power plant), so could need large solar collector, requiring large amounts of land.	Moderate-to-large industrial dischargers and power plants.	Prototypes have been constructed but technology is still within developmental stage; no current example of use for thermal mitigation.	NA	Gwynn-Jones (undated), Leffler et al. (2012)
Chillers	Chillers are mechanical devices that remove heat from the heated effluent. The five major types are differentiated by the type of compressor: absorption, reciprocating, scroll, screw, and centrifugal.	A chiller can be used essentially anywhere that power is available; chillers do not require much space and are available in a variety of configurations.	Chilling units are reliable, provide precise control of temperature, have low space requirements, and can be obtained as off-the-shelf-units; chillers are reliable in any climate.	Chillers are only viable for very small flows where a modest temperature decrease is required; chillers also require a high capital and operating cost, maintenance effort and cost.	Small dischargers or POTWs.	No known example of use of chillers for thermal mitigation.	NA	Niemi et al, (2008), Skillings Connolly (2007)
Heat exchanger	A broad category of technology to transfer heat between a source and sink. Examples include geothermal loops (buried pipes	Heat exchanger equipment	Similar to chillers; can be designed for any thermal needs. Can also be paired with chillers.	Cost, potential maintenance, geothermal requires sufficient land	Small facilities, municipal POTWs, industrial dischargers, and power plants.	Geothermal has been used for smaller systems, such as heating and cooling for office	$-$$$	Katzel (2000), NREL (2023)

Thermal Mitigation Option	General Description	Necessary Elements	Advantages	Disadvantages	Applicable for	Proposed / Hypothetical or In practice	Relative cost factors	Refs.
	that diffuse heat to groundwater or soils) or transfer heat to external cooling water.					buildings. Power plants use large-scale heat exchangers to exhaust waste heat from power generation.		

4.3.4 Selected Methods

From the methods listed in Table 4-7, EPA selected several methods for further investigation. Selection was based on coverage of the three areas of interest:

- Thermal mitigation technologies useful to small dischargers, reasonably expected to be faced with new permit requirements to reduce thermal discharge temperature or flow due to promulgation of more stringent thermal criteria, designation of the receiving water as impaired through CWA Section 303(d) listing, or climate-change related warming of ambient (intake) water temperatures;
- Thermal mitigation technologies useful to small dischargers (either existing or expected future facilities) who, currently or in the future, will discharge to effluent-dominated receiving waters including facilities located in arid conditions where water availability and consumption is a major concern; and
- Thermal mitigation technologies useful for applications to larger power plants that have traditionally relied on use of once-through-cooling-water (OTCW).

The methods selected for further evaluation included:

- Riparian shading (small dischargers);
- Flow augmentation (small dischargers);
- Hybrid wet dry cooling (small dischargers, arid conditions);
- Spray cooling (small to large dischargers);
- Helper cooling towers (large dischargers);
- Heat recovery; and
- Diffusers.

Riparian Shading

Concept

Rivers and streams gain thermal energy from many sources, including solar radiation and infrared radiation from the atmosphere, inputs of warm water, and the conduction of heat from warmer surroundings. Shade trees and vegetation in the adjoining riparian zone block a portion of the solar radiation and reduce thermal inputs. This "natural" means of thermal mitigation is implemented by planting riparian vegetation in watersheds where local vegetation has been cleared or reduced by development (Figure 4-5).

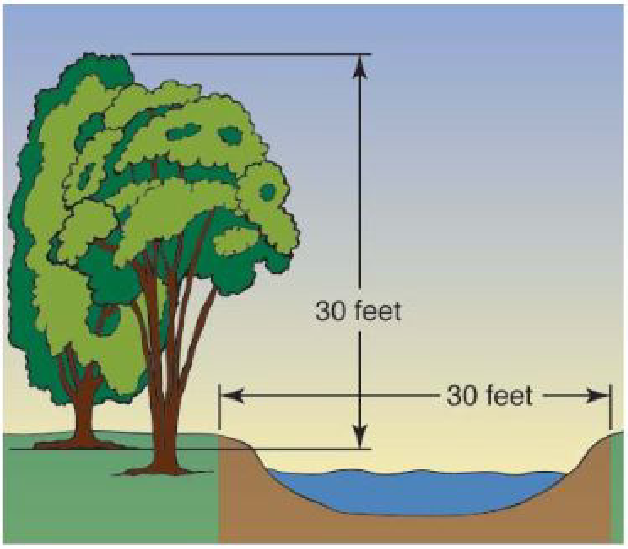

Figure 4-5. Optimal tree height for stream shading (from UM, 2010)

The amount of effective shade produced by tree plantings is expressed as the fraction of the solar radiation that is prevented from reaching the waterbody surface (University of Minnesota, 2010). For effective shading, the vegetative canopy at maturity should have at least 50 percent of the crown cover with an average canopy height of at least equal to the width of the waterbody.

Temperature/shade modeling is required to determine the amount of shade required to reduce stream temperatures to the target temperature. Some of the variables considered include: amount of solar radiation (location specific), climatic regime, height of trees when mature, planting density, stream width, stream flow, and stream buffer width (Skillings Connolly, 2007).

Advantages

Establishing forested riparian buffers is a widely practiced and effective method to stabilize or reduce stream temperatures and improve cold water fishery habitat. The method represents a holistic, watershed-level approach to water quality regulation and environmental stewardship. Riparian tree plantings provide other significant ecological services such as filtration of sediment, nutrients, pesticides, and other non-point pollution. They provide woody organic debris, an important component of trout habitat, and their root systems help stabilize stream banks and prevent erosion. In urban areas, the buffers provide a significant scenic resource for the community, similar to the benefits provided by a city park or greenway (Skillings Connolly, 2007). These secondary benefits increase public acceptance of this option.

This method's major advantage is its low cost, over time, as compared to discharge facility modifications (e.g., cooling towers) or other engineered solutions. It is a “green” solution that reduces power needs and thus decreases greenhouse gas emissions. This method has been applied in many watersheds throughout the Northeast and Northwest U.S. for stream restoration and cold water habitat enhancement and is a proven and reliable technique for mitigating thermal discharges while generating additional benefits.

Disadvantages

Some of the disadvantages of this method of thermal mitigation are: (1) unavailability or uncertainty of access to appropriate riparian areas (i.e., rights-of-way or land purchases have to be negotiated); (2) the long-term costs of establishing and maintaining healthy tree populations; (3) the significant time lag (e.g., 20 years) required before maturation of the trees provides effective shading (and cooling) of the stream; (4) reduced shading effectiveness for larger streams or rivers exceeding 20 feet in width; (5) water consumption of trees in arid areas; and (6) possible introduction of organic debris and trees to the channel may cause blockage and flooding concerns. Given the limits of stream channel width for effective shading, this method is unlikely to be effective for appreciable cooling of the thermal discharges produced by moderate to large major power plants, which require large waterbodies for cooling water. But it may remain attractive for smaller discharges, especially where green solutions are a priority or other options may not be feasible.

Applicability

This method for cooling streams is most applicable to areas that have been cleared for agriculture or development, but theoretically could be applied in other settings. This method can be used above and below the discharging facility, either upstream - to cool ambient water temperatures in tributaries supplying water to the mainstem and the facility intake, or downstream - below the discharge to reduce the thermal plume of the discharge. This method is particularly useful in maintaining or re-establishing cold water fish habitat due to its cooling effect and provisions for improving habitat and/or thermal refugia.

Example

Two POTWs (Rock Creek and Durham) conducted long-term planting programs to help reduce stream water temperatures in the Tualatin River Basin (OR) as part of the conditions for the 2004 Tualatin Basin TMDL.[25] The temperature TMDL specified an "Allowable Thermal Load" (ATL) for each facility to prevent increases in river temperature above "system potential temperature."[26] The "Thermal Load to Offset" (TLO) for each wastewater treatment facility is the amount of thermal load that exceeds the ATL. Both the ATL and TLO were calculated using an approved set of effluent and river flow/temperature condition values (CWS 2005). Most of the riparian areas in the Tualatin Basin lacked sufficient vegetation to achieve the designated system potential stream temperature. Under a Revised Temperature Management Plan agreement with the managing utility (CWS), the POTWs were responsible for restoring and/or protecting riparian vegetation to offset the warming effect of their discharges (CWS 2005).

For compliance, it was necessary to demonstrate that the amount of shade established was sufficient to meet the required portion of the TLO assigned to this method. A Heat Source model was used by the OR DEQ for estimating potential solar radiation and shade. A subroutine of Heat Source (referred to as the "Shade-A-Lator") calculated effective shade for each 100-ft stream reach (CWS 2005). Based on discussions with local landscapers, foresters, and nurseries, CWS staff estimated the canopy heights and densities expected 20 years after planting/restoration (target timeline). To account for this time lag in temperature reduction, a trading credit ratio of 0.5 was applied when determining the amount of credit associated with a particular reforestation project. The use of this trading ratio effectively meant that at 20 years, CWS would be offsetting twice as much heat via shading as their treatment plants added by discharge to the Tualatin River (CWS 2005).

These shade credits were used in a thermal energy budget that accounted for CWS activities in the Tualatin Basin. The heat budget was recalculated annually, along with progress relative to a five-year timeframe for achieving compliance with the TLO defined in the permit (the "Shade Credit Goal"). CWS initially estimated that about 35 miles of stream restoration was required to meet the goal.

Credit for creating shade was confined to activities that were independent of or exceeded other existing regulatory programs that would otherwise require plantings. Examples of shade-producing activities that could generate temperature credit are:

- Landowner incentive programs, where shade is regenerated in agricultural areas as a direct result of active management measures aimed at increasing shade;

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[25] The CWA requires that TMDL requirements be developed for pollutants that cause streams to be water quality limited. A TMDL specifies how much of a pollutant a river can receive on a daily basis and still meet WQS.

[26] System potential temperature is generally defined as a condition without human activities that disturb or remove vegetation.

- Landowner incentive programs where shade is created in forested areas under circumstances where the amount of shade either exceeds the requirements of the Oregon Forest Practices Act or the Act does not require shade; and
- Shade created under other CWA programs that furthers its environmental stewardship mission, but is not required by law. For example, shade created under a program that focuses on public land would be in this category.

In addition, an accompanying watershed permit required a system for prioritizing stream reaches where shade creation and protection should occur first; prioritizing the most sensitive beneficial use (i.e., salmonid spawning and rearing areas) (CWS 2005). A support model (RESTORE) was developed by Oregon State University and used GIS-based land use and hydrologic data input to make decisions and set priorities. Figure 4-6 shows an example of the priority areas in the Tualatin Basin.

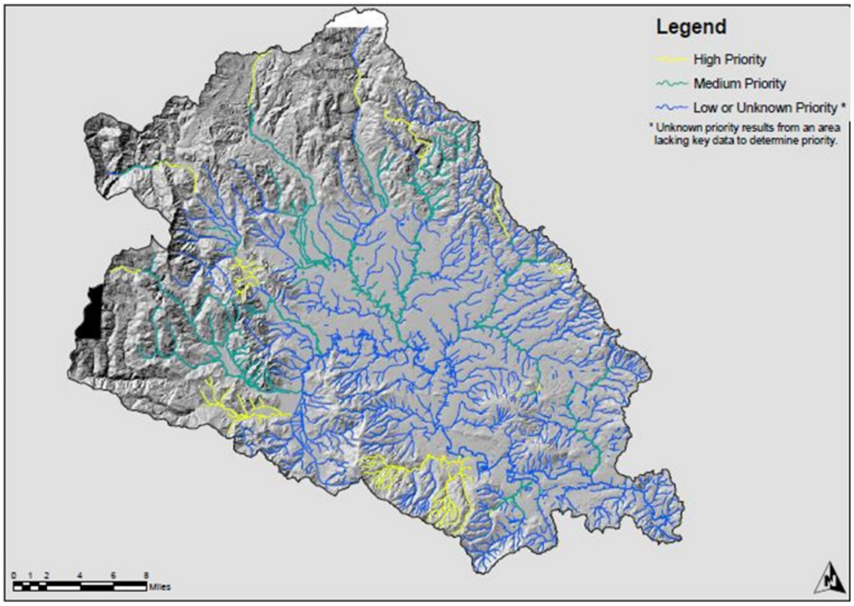

Figure 4-6. Shade Priorities in the Tualatin River Basin (CWS, 2005)

Sites where re-vegetation has occurred need further protection from a variety of threats, including invasive plant species, herbivores and dry weather. Therefore, site monitoring and maintenance played a critical role in creating and maintaining shade target goals.

During the initial NPDES permit period (2004 – 2008) around 35 miles of streamside planting were completed and CWS received a thermal credit of 295 million kilocalorie/day (Henning 2014). CWS planted an additional 13 miles of riparian zones (2009 -2013) for an additional 84 million kilocalories/day in thermal credits. Since CWS had met its TLO requirements, these excess credits were held (“banked”) to offset future discharge increases (CWS 2013 cited in Henning 2014). CWS also supported programs for riparian planting projects in urban areas (e.g., “Tree-for-All”). Between 2005 and 2010, over 500,000 trees were planted with a long term goal of four million riparian trees and shrubs by 2025 (CWS 2013 cited in Henning 2014).

Overall, CWS has been successful in meeting its permit requirement in planting trees in appropriate locations. However, despite the planting or restoration of 48 miles of riparian vegetation, water temperature conditions in the Tualatin Basin have not measuredly decreased over time (CWS 2014). In 2012, river temperatures exceeded salmonid migration and rearing temperature criteria for much of July and August, as did temperatures in the lower reaches of major tributary streams (Henning 2014). While part of this failure to meet expected levels may be due to incomplete establishment of the vegetation canopy, the more significant causal factor is the predominant role of nonpoint source thermal inputs which constitute > 88% of the total anthropogenic heat load in the watershed. This indicates that success in offsetting facility thermal loads by riparian shading may only address only a small portion of the anthropogenic heat load and that further thermal mitigation activities will be required to meet the designated system potential stream temperature.

Riparian shading continues to be applied in many northern temperature regions and elsewhere, as it not only offers thermal mitigation but potentially provides many ancillary ecological and society benefits (Neimi et al. 2008). While providing mostly a modest temperature reduction, it may be useful as part of a combined approach using several methods to achieve the desired thermal load reduction.

Flow Augmentation

Concept

Flow augmentation has many common uses and generally refers to supplementing the flow of a waterbody with flow from another source to increase volume and overall flow, and typically to improve water quality. Flow augmentation can be used to cool heated effluent by blending the thermal effluent with an available source of cooler surface water or groundwater to reduce water temperatures to meet thermal standards. Besides thermal mitigation, flow augmentation has been widely used for other purposes including complying with minimum in-stream flow requirements, improving water quality, and providing a source of reclaimed water. Two methods of flow augmentation that can be used to comply with temperature requirements are effluent temperature blending at the facility and recharging groundwater aquifers for potential reuse. Effluent temperature blending can be achieved at the facility by pumping cooling water into a mixing basin or into the discharge pipe, providing for sufficient mixing time and agitation to ensure relatively uniform reduced water temperature at the outfall (CWS 2005). Another common form of effluent temperature blending is by releasing or diverting cooler surface water from a different source(s), using the receiving water as the mixing chamber to meet temperature criteria. An example would be a controlled release from an upstream reservoir that is timed to mix with the discharge of the heated effluent.

Another type of blending would be using the heated effluent to recharge groundwater aquifers. This provides the opportunity for heat to be dissipated into groundwater in the aquifer and the surrounding earth. The flow rate of effluent discharged into surface waters may be reduced if the water in the aquifer is reclaimed for other purposes. This method can be used if there is a suitable aquifer located adjacent to the facility that provides the opportunity for reuse (EPA 2012).

Advantages

Effluent temperature blending is relatively easy to manage and regulate and can be applied on a seasonal or as needed basis. If the necessary infrastructure components (e.g., impoundments, dams, gate outlets, pumps and pipes) are already in place, then it is relatively inexpensive to operate and maintain. Thermal blending has an important ancillary benefit in increasing overall in-stream flow, often during critical periods of seasonal low flow. Reusing the effluent can reduce the temperature of the effluent while recharging aquifers, which provides a potential source for uses such as wetland restoration and agriculture (EPA 2012). Other ecological or social benefits may also be realized, as noted above. The volume of cooling water required can be estimated through relatively simple thermal balance calculations, although more thorough modeling may be required for environmental permitting (Skillings Connolly 2007).

Disadvantages

The major disadvantages of this method are the need to control and release large volumes of cool, good quality water to maintain downstream water temperatures. This may raise concerns regarding local flow augmentation source water availability and control; the design, staffing and permitting of a water release program; the economic cost of the water released (e.g., competing uses of the released water such as water supply, hydropower, recreation); and securing water or dam rights for the release. If the water must be conveyed overland to the facility, the expense of constructing a new pipeline and pump station(s) could be cost-prohibitive. Even an existing discharge line and outfall may require modification to handle the larger flow volume (Skillings Connolly 2007). In water-stressed areas, there will likely be implications for downstream resources if flow augmentation interferes with other water uses (e.g., irrigation, endangered species habitat).

Reusing the effluent to recharge an aquifer requires a suitable aquifer to be in proximity of the facility. As the distance between the aquifer and where the heated effluent is produced increases, pumping and piping costs increase. Therefore, reusing effluent for aquifer recharge becomes impractical if the location where the heated effluent is used is too far away. Additionally, the effluent may be required to meet additional water quality criteria before it can be used as reclaimed water.

Applicability

The most important factor is the ready availability of a large volume of cooler water, so this method is generally confined to watersheds with an existing system of upstream impoundments. The temperature of the released water must be significantly cooler than that of the thermal effluent. This method could be advantageous for a facility where land for implementing other types of thermal mitigation is severely constrained or not feasible to meet the degree of cooling needed (e.g., maintenance of critical salmonid spawning and rearing water temperatures for rivers in the Pacific Northwest). This method would not be feasible to cool the large volume of thermal effluent discharged by most large power plants, however.

Reusing the effluent for aquifer recharge requires a suitable aquifer in close proximately to the plant. Additionally, reusing the effluent may be advantageous in areas with nearby agriculture or other uses for reclaimed water. This could include areas with high agricultural activity and a drier climate.

Example

A variation of this method was implemented in the Tualatin River Basin in northwest Oregon as part of 2004 NPDES permit. During the summer months, low river flows are correlated with higher temperatures and reduced water quality. Water released from upstream reservoirs during mid-summer augments the flow in the Tualatin River. The release is scaled to cool a portion of the thermal effluent from two POTWs in the watershed, as well as restore instream flow and improve aquatic habitat.[27] Flow augmentation and the two POTWs discharges are a major component of summer streamflow on the Tualatin River, usually exceeding natural flow (CWS 2013). This program, together with the riparian shading program described above, is a part of a watershed–based thermal mitigation effort (CWS 2005, Henning 2014).

Effluent temperature blending releases generally occur from July through October each year, with the exact timing of releases dependent upon Tualatin River streamflow response to weather conditions (CWS 2014). While most releases directly affect the Tualatin River, CWS has also partnered with the local Tualatin Valley Irrigation District on several tributary flow restoration projects (CWS 2013).

Overall, temperature blending releases have been successfully implemented and are important to maintaining flow. CWS is highly dependent on flow augmentation to offset POTW releases. Flow augmentation accounted for 73.5% of the thermal credits claimed by CWS in 2013 (CWS 2014). The population of the Tualatin basin is increasing. It is projected that an additional 40,000 acre-feet of water will be needed by 2050 (Henning 2014). As anthropogenic water use grows, increasing the height of existing dam structures to increase water storage is being studied (Henning 2014).

Despite the seasonal flow, current summer water temperatures are not being stabilized or decreasing in the Tualatin River. As described above, the main reason is that offsetting POTW release only addresses a small portion of the overall heat load which is dominated by non-point sources. Nevertheless, for some smaller facilities with abundant water supplies, effluent temperature blending could potentially be used as part of a combination of thermal mitigation methods.

The Talking Water Gardens Project is a collaborative POTW project between the cities of Albany, OR and Millersburg, OR to meet TMDL requirements for temperature in the Willamette River by using constructed wetlands as the final treatment step for wastewater effluent. The project includes 37 acres of constructed wetlands to cool the water prior to discharge while providing groundwater recharge to the local aquifer. A Net Environmental Benefits Analysis calculated that the wetlands have an environmental benefit score that is 2.5 times higher compared to a conventional wastewater treatment methods (EPA 2015a).

Hybrid Cooling Systems

National water resources will be impacted as climate change is expected to make droughts in many interior regions more severe, reduce water availability, and increase the ambient temperature of lakes, streams, and rivers. These effects may be particularly severe in arid or semi-arid climates, including areas where natural gas resources are currently being tapped. Future expansion of power plants, POTWs, or other dischargers in these water-poor regions may depend on use of thermal mitigation technologies that place a premium on the ability to operate with limited water supply. Use of wet-dry hybrid cooling towers is one possible solution to meet this challenge.

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[27] One alternative version of influent cooling by injection of a thermal discharge into an adjacent hyporheic zone for cooling purposes (Lancaster et al., 2005) has been reviewed by EPA Region 10 who found that this option disrupts the functioning of the thermal regime of a river and would not be environmentally sound and would be inconsistent with CWA regulations.

Concept

Hybrid cooling systems combine dry cooling and wet cooling technologies to reduce water use relative to wet systems while improving hot-weather performance relative to dry systems. The two primary uses for hybrid systems are for water conservation or for plume abatement.[28] For purposes of this document, EPA only considered hybrid systems designed primarily for water conservation.

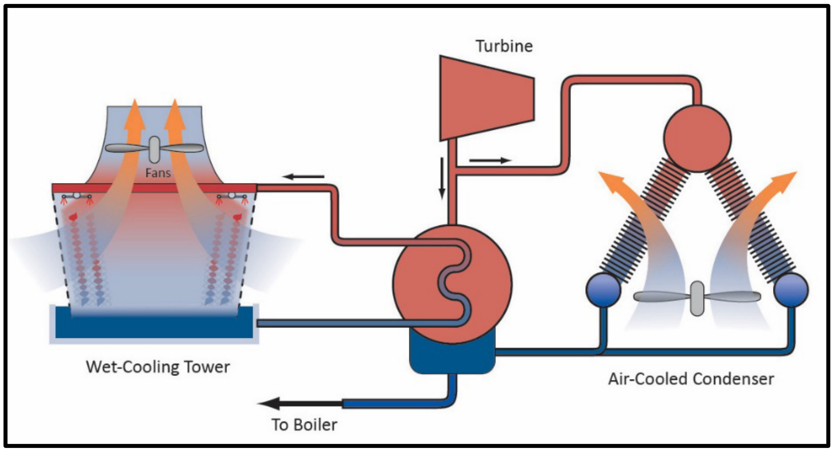

Figure 4-7. Hybrid Cooling System (from Bushart, 2014).

Hybrid systems, designed principally for water conservation (or operation in arid climates), are primarily dry cooling systems with a small wet cooling capacity to provide additional cooling during the hottest periods of the year (Figure 4-7). A limited amount of water is used during hotter periods to mitigate the large losses in steam cycle capacity and plant efficiency associated with an all-dry cooling operation. Specifically, the cooling tower uses small amounts of water to pre-cool the ambient air streaming into the tower, reducing the air temperature toward the critical wet bulb temperature, the minimum temperature that can be reached by evaporative cooling. The cooler air then passes through heat exchangers which are able to extract more heat (Engineers Australia, 2015).

Advantages

Hybrid systems can significantly reduce the volume of cooling water consumed when compared to conventional wet recirculating or OTCW systems. These systems are reported to have the potential for more than 50% water savings (typical range is from 20 to 80%) compared to wet cooling towers (California Energy Commission (CEC) 2002, Bushart, 2014). They achieve substantial efficiency and capacity advantages during hot weather when compared to an all-dry cooling system.

Modelling indicates that a hybrid system can increase net power output up to 20% over a dry-only cooling system by using wet cooling during periods of high ambient temperature (Gwynn-Jones et al., undated). Use of a hybrid system increases the range of ambient temperatures under which the tower can operate. This increased efficiency allows the tower to be smaller (thus built at lower cost) and increases the total plant power output over the life of the tower (Gwynn-Jones et al., undated).

Disadvantages

A hybrid cooling system is more expensive compared to recirculated wet cooling towers alone, and significant amounts of water may still be needed, particularly during the summer (Bushart, 2014). Since these times would typically coincide with periods of peak electricity consumption, a decline in power

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[28] Plume abatement towers are essentially all-wet systems that employ a small amount of dry cooling to dry out the tower exhaust plume during cold, high-humidity periods when the plumes are likely to be visible (CEC, 2002). Most hybrids systems currently used in the U.S. are designed primarily for plume abatement.

production could hinder the ability to meet customer demand and a potentially pose a significant revenue loss (Micheletti and Burns, 2002). A hybrid system can also be subject to all of the operation and maintenance issues associated with both types of cooling systems (e.g., fan power, blowdown, cooling water treatment, and freeze protection).

There is relatively little information regarding installation of hybrid cooling for water conservation in major power plants. CEC (2002) cited a large water conservation tower installed on a 550 megawatt (MW) unit of the coal-fired San Juan Plant in San Juan, NM, in 1977, but little additional information was given. Reliable engineering and costing information on this type of cooling system for large-scale utilization appears to be limited. Micheletti and Burns (2002) suggested that the costs of installing a hybrid system were similar to a direct dry system and that operation and maintenance costs were similar or higher.

Applicability

A hybrid cooling system is most suitable for sites where significant water conservation is required, but some water is still available for partial evaporative cooling during high temperature periods. The major advantages of hybrid systems include: (1) reduced or eliminated water consumption; (2) low power consumption (avoids powered fans); and (3) simple tower structure and low construction cost. In addition to use in natural gas fired systems, a hybrid cooling system can also be incorporated into small scale thermal power plants (1-10 MW) using renewable sources (geothermal, biomass and solar) (Gwynn-Jones et al., undated).

Example

Innovative hybrid cooling technology is being developed in Australia to provide small scale power generation options to remote communities (Engineers Australia 2015). A basic design requirement is that these technologies have cooling towers that work efficiently at small scale without consuming excessive amounts of water. Researchers at the University of Queensland’s Geothermal Centre have developed a polymer-steel cooling tower with a flexible design allowing operation under dry, wet, and hybrid cooling modes and which can function using non-powered natural draft (Gwynn-Jones et al., undated).

The demonstration hybrid cooling tower is sufficiently large enough to provide power for up to 1,000 people (Figure 4-8). Some of the innovative features included:

- Flexible cooling modes, including hybrid cooling, allowing the tower design to be tailored to site-specific water availability;
- Windbreak walls, allowing the hybrid tower to achieve consistent performance at any scale even in the presence of crosswinds;
- High efficiency heat exchangers providing excellent cooling performance; and

Figure 4-8. Demonstration Hybrid Cooling Unit (from Gwynn et al., undated).

- Modular steel and polymer design, reducing construction costs and time, and improving capability for isolated deployments, thereby enabling small-scale natural draft design.

The demonstration tower is primarily a research facility but provides benefits for application for remote area thermal power generation in arid or water-stressed locales.

Spray Cooling Systems

Concept

Spray cooling systems use facilitated evaporative cooling to remove excess heat from a thermal effluent. The effluent is sprayed by nozzles into the atmosphere, producing small droplets which effectively transfer moisture and heat into the air, thus cooling the remaining water. The operative physical cooling principle is much the same as in a cooling tower. Spray cooling requires one to multiple spraying units, consisting of pump, motor, manifold, and nozzles (Skillings Connolly, 2007). These units are used as fixed arrays or can be employed on a floating platform (Figure 4-9). Other engineering considerations include the use of pumps efficient at low head (20 to 23 feet of water) and high flow operating conditions.

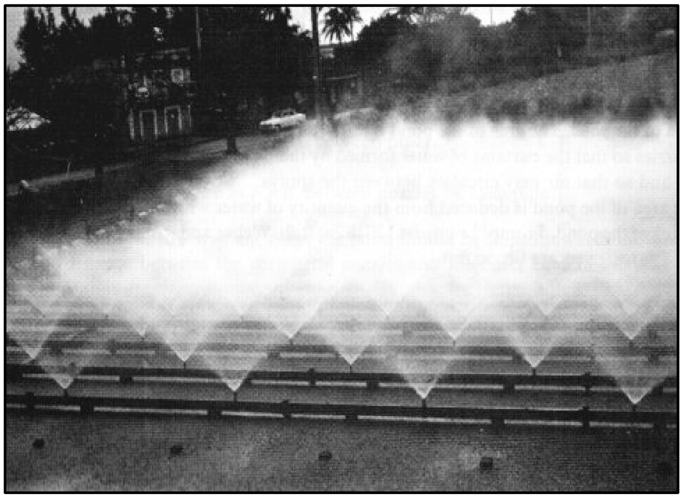

Figure 4-9. Spray Pond Fixed Array

Ambient temperature and relative humidity are critical factors for effective heat transfer rates. The theoretical level of cooling achievable through an evaporative system depends on the difference between the effluent temperature and the ambient wet bulb temperature, surface area of water in contact with the air, the relative velocities of the air and water droplets during contact, and the amount of time the effluent is in contact with the air (Skillings Connolly, 2007). Spray pond performance is particularly sensitive to the type and size aperture of the spray nozzle used. Nozzle size should be selected to avoid clogging and provide for a fine spray of small droplets (e.g., 2 mm diameter). The spray trajectory is also an important part of the cooling equation because it dictates the average velocity and air residence time of each droplet (Leffler et al., 2012).

Advantages

Spray cooling ponds provide an effective means to reduce thermal content and have much smaller land requirements when compared to static cooling ponds or canals. This approach can be used for a variety of facilities and is easily installed within existing cooling ponds or canals. Spraying ponds can be installed as part of an intermediate treatment within the plant (see Zellstoff-Celgar example below) or just prior to discharge. It can be used seasonally or in combination with other thermal mitigation methods.

Leffler et al (2012) consider spray ponds to be a good option if land resources are limited and supply of the required pumping power is not a significant concern. The surface area requirement for spray cooling is much less than that needed for a static cooling pond and under certain circumstance can be as low as 5% (Skillings and Connolly, 2007) but can be substantial for larger facilities. In addition to cooling the effluent, spraying also aerates the effluent. With regard to water consumption, spray cooling ponds evaporate water at a rate comparable to a typical cooling tower (Leffler et al., 2012).

Disadvantages

Spray cooling consumes power for pumping and spraying the effluent, and therefore presents a more expensive approach than a static cooling pond. System performance is highly susceptible to local climate conditions. Under certain circumstances, fog may form and cause "drift" from the spray pond, impairing visibility or create condensation on nearby buildings, vehicles, or equipment (Skillings Connolly, 2007). This method may require costlier corrosion resistant materials to deal with continuous exposure of the motor to very humid conditions, along with higher maintenance cost.

High ambient relative humidity results in poor separation between the temperature of the effluent and the air's wet bulb temperature, and can greatly reduce the evaporative heat transfer from the spray. In northern climates, special provisions may be necessary to prevent the equipment from freezing in winter. This method of thermal mitigation is likely to less applicable to arid or water-stressed settings, as the water lost to evaporation is no longer available for return to the receiving water.

Application of this method as the sole source of thermal mitigation for a large power plant would require considerable land and energy. Leffler et al. 2012 estimated that cooling the effluent for a 500 MW power plant by 10^{o}C (i.e., 45 ºC to 35 ºC) would require approximately 14,600 nozzles arrayed on a 90.4 acre pond.

Applicability

Spray cooling units would be appropriate in a location where there is (1) insufficient space for a static cooling pond; (2) the water supply is not limited; (3) there is good power availability and/or (4) where additional DO in the effluent is a desired result. Spraying units can be easily deployed on existing ponds and canals and can be used as needed, with an adjustable number of units. Spray ponds are deployed as thermal mitigation over a range of application, from small POTWs to larger dischargers. For example, spray ponds were identified as an attractive method of providing the "ultimate heat sink" with application in several nuclear power plants (Codell, 1986).

The selection of spray cooling for thermal mitigation should consider the range of expected climatic conditions at the facility. In southern regions of the U.S. there may be difficulty in maintaining at least a 10°C difference between the effluent temperature and ambient wet bulb temperature[29] during summer month due to the reduced evaporative cooling effectiveness at high temperature. In northern regions, cold temperatures and the potential for impaired or frozen sprayers need to be considered.

Examples

The Zellstoff Celgar pulp mill is an example of a large industrial application of spray ponds (Figure 4-10). The mill is located along the upper Columbia River near Castlegar, B.C. (Canada) and consumes more than 2.6 million m^3 of wood fiber annually, producing pulp that is sold worldwide for use in tissue, toweling and hygiene products (Kootenay Business, 2015).

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[29] The temperature of a wet-bulb thermometer when the heat leaving the wet bulb from evaporative cooling is equal to the heat transferred to the wet bulb by convective heat transfer from the surrounding air.

The plant produces 15 to 20 MGD of process water and uses five 75-horsepower spray cooling units after the primary clarifier and before the aeration basin (Aerators Inc., cited by Skillings Connolly, 2007).

Figure 4-10. Zellstoff-Celgar Pulp Plant, Castelgar, B.C.

The thermal effluent enters the spray cooling pond at 55°C and is cooled to 35°C. The 22-feet deep, 4.5 acre spray cooling basin operates year round. Ambient temperatures range from 0°F in winter to 100°F in summer. Spray ponds were selected as the preferred thermal mitigation option for this facility because of: (1) severe land availability constraints made evaporation ponds infeasible and (2) there were concerns about the high capital cost of a cooling tower and (3) uncertainty regarding the dissipation of the steam plume in the enclosed valley.

The Dresden Nuclear Generating Station provides an example of the application of spray ponds in a large power plant. In the 1980s-1990s, their heated effluent discharged into a two-mile-long spray canal containing floating spray modules to expedite cooling (ComEd, 1980). After a retrofit of the plant, the spray cooling was replaced by 32 mechanical cooling towers (U.S. Nuclear Regulatory Commission (USNRC), 2004). Further description of the use of these seasonal helper cooling towers are described below.

There are many examples of application of spray ponds in small discharging facilities (often in a dual role of thermal mitigation and oxygenation). Skillings Connolly (2007) cited the example of a small POTW in Granite Falls, WA, that used three floating surface aerators on its effluent just ahead of the UV disinfection system. This arrangement was expected to cool the small effluent flow by approximately 1°C.

Helper Cooling Towers

Concept

Power plants that historically relied on open-cycle cooling face significant challenges in meeting the regulatory requirements with respect to protecting aquatic life, shrinking the thermal plume, and reducing consumptive water use. In many cases, plants designed after the 1970s have been designed to operate in a closed-cycle mode. However, some older plants with OTCW have been able to comply with more stringent thermal effluent limitation through installation and use of a “helper cooling tower.”

A helper cooling tower is an auxiliary cooling tower (either wet or dry cooling) of sufficient capacity to lower the discharge effluent temperature to a level acceptable for discharge into the receiving water (SPX, 2009). For facilities where permit thermal limits are only slightly or occasionally exceeded, the scaling of the helper tower is designed for a smaller capacity that would be typically required if the full thermal load was to be dissipated (Figure 4-11). Further, under certain combinations of heat load and ambient water temperature, the plant's thermal effluent temperature may meet thermal standards, in which case the helper tower may be shut down and its operating costs avoided (SPX, 2009).

Advantages

The main advantage is that helper cooling towers can be installed in a power plant using OTCW to achieve seasonal compliance with discharge effluent thermal limitations. This can help avoid or postpone the very high costs associated with converting to a closed-cycle cooling system (which may not be economically or technically feasible for some facilities). Facilities already operating with a flexible cooling water system (i.e., can operate as either closed-cycle or once through) may also employ a helper tower seasonally to reduce thermal loading and cooling water discharge temperatures. The helper tower(s), used in combination with closed-cycle systems, provide more operating flexibility, allowing plants to shift between closed-cycle and open-cycle with helper tower(s) during certain periods of the year.

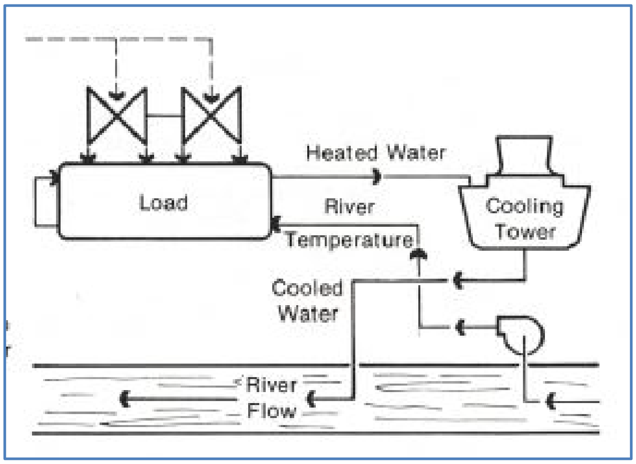

Figure 4-11. Schematic Design Showing Helper Cooling Tower (from SPX, 2009)

Cooling towers are relatively uncomplicated in operation and provide predictable cooling performance (Skillings Connolly, 2007). The design, engineering, and costs of helper cooling towers are well established since they rely on existing technologies (wet or dry). Scaling of the cooling unit(s) can be refined to provide sufficient cooling capacity appropriate to the facility's site-specific conditions. Helper cooling towers can be installed as a set of multiple units or modules, where some or all of the units can be used, depending on ambient water temperatures, to allow more cost-effective response to cooling needs (SPX, 2009).

Disadvantages

Helper cooling towers require sufficient land and infrastructure on the existing facility site. Construction of helper towers is more cost-effective than conversion to a complete closed-cycle cooling system, but this technology can still be very expensive (see PPL example below). Use of cooling towers requires more power and operation maintenance (e.g., removal of biological growth) and they may only be needed for short periods of the year. They are less effective in humid locations and the drift from the tower can impact visibility or deposit materials on nearby surfaces and land.

Applicability

Helper cooling towers are often used for power plants along rivers and inland waters where the impact of thermal discharges will likely have greater influence as compared to discharges to marine environments. Cooling towers are more effective in climates where there is an expected difference of at least 10ºC or more between thermal discharge and the ambient wet bulb temperature (Skillings Connolly, 2007). This method is applicable for a wide variety of moderate to larger dischargers since the scaling of the helper tower can be matched to the facility's cooling needs. However, due to the construction and maintenance expense, small dischargers may want to consider other methods of thermal mitigation.

Examples

PPL Corporation's Brunner Island plant (York County, PA) is a three-unit, 1,546-MW plant (Figure 4-12). PPL invested approximately $100 million to install forced-draft cooling towers to reduce the thermal loading and discharge temperatur e to the Susquehanna River (Mallory, 2012). The new cooling towers began operation in April 2010. The 34-cell cooling tower requires four 3,500-hp pumps to deliver about 0.5 MG per minute. The cooling towers are used during the nine warmest months of the year, from March through November.

Figure 4-12. PPL Brunner Island Plant with Helper Cooling Tower (from PPL Corporation)

Dresden Nuclear Generation Station, located at the headwaters of the Illinois River, is another example of the application of helper cooling towers. The Station utilizes water from the Kankakee River and the Des Plaines River for cooling, and the cooling water is discharged to the Illinois and Kankakee River (USNRC, 2004).

Dresden Nuclear Generation Station Units 2 and 3 can be operated in closed-cycle mode at any time of the year, but normally this mode is used from October through mid-June. During the summer, a series of 36 mechanical draft cooling tower cells operate, as necessary, to maintain water temperatures within the limits of Dresden's permit. These cooling towers have a maximum water withdrawal capacity of 40m^3/s (630,000 gpm) and, on average, total evaporative losses of 0.9 m^3/s (14,400 gpm) when both units are operating. It is interesting to note that the mechanical cooling towers replaced a spray cooling pond that was previously employed at the station (ComEd, 1980).

Heat Recovery

Concept

Heat recovery equipment allows heat from the effluent to be transferred to other processes or applications where heating is desirable, thus lowering the effluent's temperature prior to discharge into receiving waters (Mikkonen et al., 2013). Heat from the effluent can be transferred to another process stream using either a heat exchanger or a heat pump. (Mikkonen et al., 2013).

A heat exchanger is a piece of equipment designed to transfer heat between two fluids and allows energy from the effluent to be directly transferred to another flow stream. The reduction in temperature of the effluent stream depends on the thermal properties of both fluids, the type of heat exchanger used and the heat transfer surface area of the heat exchanger. A heat exchanger is limited by the flow rate and temperature of the process stream that heat is being transferred to because it can only reduce the temperature of the effluent stream to approach thermodynamic equilibrium between the two streams. The properties of the heated effluent and process stream should be evaluated to determine if a heat exchanger alone can provide sufficient cooling to the effluent stream and is sufficient to meet the temperature requirements specified in the facility's permit.

Unlike a heat exchanger, a heat pump (see Figure 4-13) can transfer heat from effluent to a process stream that is at a higher temperature than the effluent stream. However, a heat pump requires energy to power a compressor, and is more complicated to operate than a heat exchanger alone. Since heat pumps can transfer heat from a heated effluent stream to a hotter flow stream, they can be used to heat water for buildings as well as industrial process streams. Most existing heat recovery systems use heat pumps for heating and cooling networks in buildings (Nagpal et al., 2021).

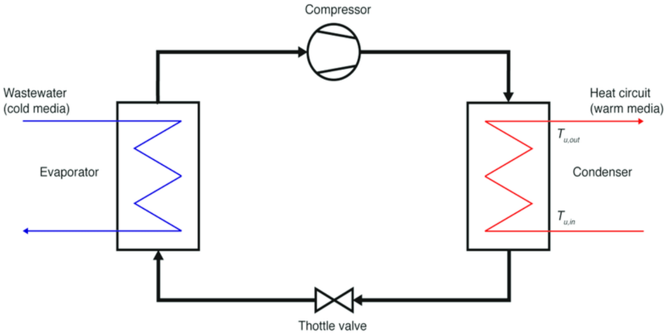

Figure 4-13. Schematic Design Showing a Heat Pump System (from Arnell et al., 2012)

Advantages

The main advantage to recovering heat from effluent is that it can effectively reduce the temperature of the effluent stream to achieve compliance with effluent limits for temperature while also reducing the energy requirements for the permitted facility, neighboring industrial facilities or nearby buildings. Low temperature waste streams such as effluent discharges represent huge sums of energy that are lost annually (Muller et al., 2013). Recovering heat from these streams can result in a lower life cycle cost for the facility, as the savings in energy costs offset the capital costs of the heat exchanger or heat pump and the costs associated with the increased energy requirements, or from revenue generated by selling the effluent to another facility.

Disadvantages

The major disadvantage of a using heat recovery to cool effluent is that it requires a process stream where heating is desired at the facility, or at another facility in proximity. Pumping and piping equipment are required to transport effluent to the heat exchanger or heat pump where the other process stream is located. As the distance between where the heated effluent is produced and where the heated effluent is used for heat recovery increases, the costs for pumping and piping increase. Therefore, heat recovery becomes impractical if the location where the heated effluent is used is too far away (Nagpal et al., 2021).

Installing either a heat exchanger or a heat pump increases the capital costs of the facility. Both systems also increase the overall maintenance and costs for the facility. A heat pump system requires additional energy to power a compressor, although this is likely outweighed by the energy recovered from the effluent. An overall life cycle cost analysis is required to determine if the cost savings from reducing heating energy requirements outweigh the increased capital and operational costs for the heat recovery equipment.

A heat recovery system may not be able to handle changes to the flow rate or temperature of the effluent. Therefore, facilities with effluent flow rates and temperatures that are variable may need to include additional effluent cooling measures to achieve compliance with their permit during peak flow conditions or conditions when the effluent is at an abnormally high temperature.

Applicability

Heat recovery should be considered at facilities that have another process stream that requires heating or are located near other facilities that have a process stream that requires heating. In general, a heat exchanger is more likely to be suitable for smaller facilities, while a heat pump is likely to be more suitable in medium to large facilities. In addition to heating process streams in industrial facilities, heat recovered from effluent can be used to heat water in buildings. Processes that have little variance in the flow rate or temperature in their effluent are more suited to this method than processes with variable effluent flow rates and temperatures.

Examples

A 2013 review from Rutgers University examined the economics and scalability of heat pump installations at 22 wastewater treatment facilities in the U.S. The effluent temperatures at each of the facilities ranged from 50°C to 60°C. The heat pumps had an average coefficient of performance of 3.5, meaning that they recovered 3.5 times as much energy from the effluent stream as energy that was consumed by the compressor. Most of the 22 facilities evaluated used the recovered heat to heat buildings, however some special cases were identified. A POTW in Renton, WA used the heat recovered from the effluent to heat the on-site anaerobic digesters. Another POTW in Avon, CO used the heat recovered to heat the water in a local swimming pool (Muller et al., 2013). Six of the facilities that were examined provided project cost data to calculate the payback period for the facilities, which ranged from approximately four years for a POTW in Washington County, NY to approximately 18 years for a POTW in Saco, ME. The review found that the payback period generally increased as the capital cost of the heat pump increased (Muller et al., 2013).

The largest heat recovery system in the world extracts heat from treated wastewater effluent is the Hammarbyverket plant located in Stockholm, Sweden. The plant recovers heat from treated wastewater with heat pumps and uses it to heat residential buildings. The heat recovery plant receives a flow rate between 25 MGD and 114 MGD of treated effluent from a nearby wastewater treatment plant, with temperatures between 7°C and 22°C. The heat pumps cool the effluent to between 1°C and 5°C, and produce 1,235 gigawatt hours of energy annually, which is enough to heat approximately 95,000 residential buildings (Mikkonen et al., 2013).

Diffusers

Concept

A diffuser is a device that is designed to discharge effluent into a receiving water through a series of nozzles at high linear velocities, rather than a single discharge point. This improves the effluent and receiving water mixing process, which reduces elevated receiving water temperatures around the point of discharge. Generally, four main types of diffusers are used to discharge heated effluent into receiving waters (Roberts, 2011). Figure 4-14 shows how each of the four main types of diffusers operates.

Coflowing diffusers run perpendicular to the shoreline of the receiving water, and have nozzles that point downstream of the current. Coflowing diffusers are generally used for discharges to rivers and other recieving waters that are flowing in one direction.

Tee diffusers run parallel to the shoreline and have nozzles that point away from the shoreline. Tee diffusers are generally used in large waterbodies with currents that flow both ways, such as opean coasts.

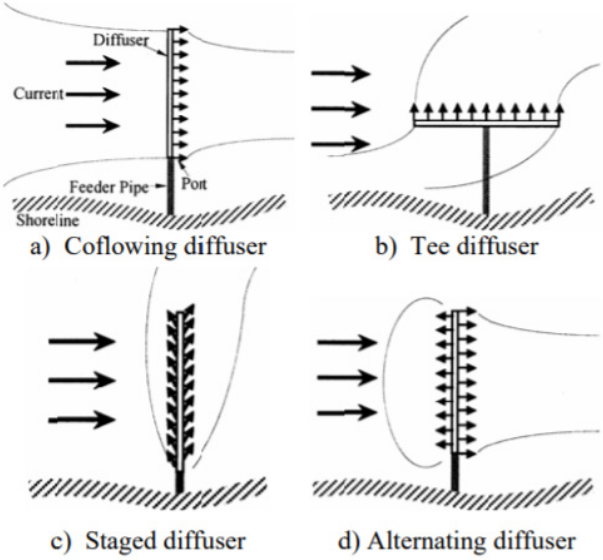

Figure 4-14. Basic types of multiport diffusers for thermal discharges (Roberts, 2011)

Staged diffusers run perpendicular to the shore line of the receiving water, and have nozzles that point offshore on either side of the diffuser. This type of diffuser is also used in large waterbodies, and is an alternative to a tee diffuser.

Alternating diffusers run perpendicular to the shoreline and have nozzles on both sides of the diffuser. Alternating diffusers are less common, but are generally used in receiving waterbodies with low currents such as lakes.

Advantages

A diffuser system allows the effluent to mix with receiving waters more rapidly, which reduces the area of water that has an elevated temperature around the location of the discharge. Some water quality criteria specify that rapid and complete mixing, or a larger dilution allowance, can be assumed for developing water quality based effluent limits (WQBELs) in permits for outfalls that are equipped a diffuser (EPA, 2010). This allows facilities to achieve compliance with temperature effluent limits more easily, while also protecting the water quality of the receiving water. Additionally, a diffuser can help a facility to achieve compliance with other permit WQBELs by improving mixing.

Disadvantages

Diffusers are designed to increase mixing between the effluent and the receiving water, but diffusers do not reduce the overall temperature rise of the receiving water in areas where mixing is complete. In particular, diffusers may need to be used in conjunction with other methods for discharges to smaller waterbodies such as a river or a lake, where effluent is more likely to have a significant effect on the temperature of the receiving river water once they are completely mixed.

The mixing process between the effluent and the receiving water is complicated and may require modelling to understand the temperature profile within the mixing zone. Developing a mathematical model may require using software such as UM3 of Visual Plumes or CORMIX (see Section 4.1 for more information on models). In some cases, the complex 3-D nature of the mixing zone may require a physical model to be constructed (Roberts 2011).

Applicability

Diffusers are widely applicable to facilities with heated effluent because they decrease the area of the receiving water mixing zone. A diffuser should be used when better mixing in the receiving water is needed to eliminate localized high temperature areas near the outfall. As discussed above, the type of diffuser that should be used is largely dependent on the size and current patterns of the receiving water. A diffuser cannot reduce the overall temperature rise of the receiving water once mixing is complete.

Examples

A physical model was developed during construction of the Banha Power Plant in Dakhleya, Egypt to evaluate the effectiveness of a proposed diffuser system on the receiving water temperature in the mixing zone of the outfall. The model first tested an open channel outfall without a diffuser and found that the thermal plume caused a temperature rise of over 5°C across a 4,500 m^2 area, which would not comply with local environmental law. The model then tested installing a 24 nozzle tee diffuser and found that the area where the thermal plume would cause a temperature rise of over 5°C would be reduced to 600 m^2, and would bring the plant into compliance (Shawky et al. 2012).

A proposed mine in the Northwest Territories of Canada that would be discharging excess water into a small lake performed modelling using CORMIX to evaluate whether a diffuser would achieve compliance with the local effluent limits for temperature. The modelling found that the diffuser achieved high levels of mixing in the near field region and provided some confidence that the diffuser would produce enough mixing within a 50 m radius (the local mixing zone allowance) to achieve compliance with local regulations (Fortune Minerals, 2011).

A POTW in Cedar Rapids, IA redesigned their outfall to include a diffuser. This approach allowed the facility to increase their dilution allowance because the diffuser provided more rapid mixing. Representatives of the plant indicated that the diffuser reduced the heat dissipation distance downstream of the outfall from over a mile to 100 yards (Skillings Connolly, 2007).

The City of Centralia, WA employs a diffuser for discharges of a POTW to the Chehalis River to reduce the size of the mixing zone with elevated temperatures around the outfall. The diffuser has eight 16-inch ports, with four in use at a time (Skillings Connolly, 2007). The diffuser is installed to comply with the conditions in the facilities NPDES permit that require mixing zones to be minimized (WA Department of Ecology, 2021).

Assumptions and Uncertainty

The information provided in this document provides useful information to facility permit applicants considering thermal mitigation options and regulatory permit writers evaluating these methods. However, use of the data is subject to several key assumptions and sources of uncertainty, including:

- Documented thermal mitigation methods came from multiple sources, including: scientific research articles, government and non-governmental organization reports and websites, NPDES permits and supporting documents, vendors' information, etc. The uneven quality assurance and potential biases of these sources should be considered when evaluating their results or conclusions;
- In selecting thermal mitigation methods to evaluate, EPA gave preference to those methods with more engineering and costing information based on actual construction and implementation of the method;
- Due to the variety of thermal mitigation methods, age of installation and facility site-specific conditions, direct comparison of costs in current dollars was beyond the scope of this document and only relative costs were identified in Table 4-7;
- Many of the identified options were proposed with small dischargers in mind, so there is considerable uncertainty whether such methods could be successfully scaled up for use by moderate-to-large dischargers;
- Thermal mitigation methods may be combined to reduce effluent water temperature within and downstream of the facility. A combination of methods may be used seasonally to optimize plant performance while still meeting regulatory standards. EPA did not attempt to identify the large number of potential combinations of method that could be utilized; and
- EPA generally considered facilities generating power through use of nuclear materials or fossil fuels. However, thermal mitigation methods may also be applied to discharges from solar or geothermal-powered facilities or plant.

Due to the wide spectrum of dischargers, flow conditions, and resources available, these sources of uncertainty should be considered on a site-specific basis when evaluating potential thermal mitigation methods.

Summary

EPA reviewed over 20 methods of thermal mitigation, representing a wide spectrum of available and theoretical solutions, and selected seven for further investigation. These included:

- Riparian shading;
- Flow augmentation;
- Hybrid cooling systems;
- Spray cooling;
- Helper cooling towers
- Heat recovery; and
- Diffusers

Some of these methods are widely practiced (spray cooling, helper cooling towers, and diffusers) while other (riparian shading, flow augmentation, and hybrid cooling systems) are more limited in current application. However, any of these may be appropriate for a given facility. One of the current factors leading to a reduction in thermal pollution is the phasing out or retirement of many fossil fuel or nuclear powered generating stations that relied principally on OTCW - due to unfavorable economics or technological obsolescence or both. In addition, the rapid proliferation of natural gas or sustainable power (solar or wind) could reduce or eliminate the need for a large source of water for cooling purposes. These factors, together with the expected ambient water temperature increases predicted with climate change, suggest that future thermal mitigation methodologies for small-to-moderate dischargers are likely to become increasingly important.

4.3.5 Section 4.3 References

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4.4 Appendix C to Section 4.0: Detailed Technical Information on Thermal Mixing Models

4.4.1 CORMIX

Model Key Components and Processes

CORMIX simulates the geometry and dilution of the near-field mixing zone and can be applied to predict far-field plume behavior (Durkee, 2012). To appropriately model mixing zones, CORMIX has four core subsystems that each caters to different discharge outfall designs (Akar and Jirka, 1991; CORMIX, 2021a):

- CORMIX1 is built specifically for single port outfalls with positively, neutrally, or negatively buoyant discharges,
- CORMIX2 is best for submerged multiport diffuser discharges with positively, neutrally, or negatively buoyant discharges, and
- CORMIX3 models surface outfalls that have positively or neutrally buoyant discharges relative to receiving waters (Durkee, 2012; CORMIX, 2021b; 2021c; 2021d).
- DHYDRO is designed to simulate the discharge of high density brines and sediment discharges into unbounded coastal environments, and is able to simulate any of the single or multiport outfall configurations used in the other three modules (Donneker and Jirka, 2007).

CORMIX1 and CORMIX2 can both model positively, neutrally, or negatively buoyant discharge densities, as long as the receiving waters fit one of the three stratification profiles that are provided within the model (CORMIX, 2021b, 2021c). Table 4-8 shows additional key components and processes for the CORMIX model and subsystems.

Table 4-8. CORMIX Key Components and Processes

Key component/process	CORMIX	References
Unsteady state	Yes	CORMIX, 2021b CORMIX, 2021c CORMIX, 2021d CORMIX, 2021e Doneker and Jirka, 2007 Morelissen et al., 2013
Boundary interactions	Yes	
Density currents	CORMIX1 and CORMIX2: positively, neutrally, or negatively buoyant discharge. CORMIX3: positively and neutrally buoyant discharge. DYHYDOR: negatively buoyant discharge	
Dimensions	2-D and 3-D	
Time steps	Set by the user	
Unstratified vs stratified ambient	Unstratified or stratified	
Outfall designs/discharge configurations	CORMIX1: single port outfalls. CORMIX2: multiport outfalls. CORMIX3: surface outfalls. DHYDRO: single port, multiport, or surface outfalls.	

CORMIX is a finite difference model. It can model mixing zones in both 2-D and 3-D and uses length scales to classify flow regimes (Doneker and Jirka, 2007). Originally, CORMIX assumed steady ambient flow conditions, but modern versions are able to model receiving waters affected by tides and other unsteady flow conditions (Doneker and Jirka, 2007). The model incorporates boundary interactions, which occur when the discharge comes into contact with and is affected by channel boundaries or surfaces. Boundary interactions help determine if the ambient flow is steady or unsteady (Doneker and Jirka, 2007).

In addition to its core algorithms, there are several advanced versions of the CORMIX v12.0 system that extend its usability (at extra cost). These plug-ins include (CORMIX, 2021f):

- CorGIS (a EPA BASINS – CORMIX data linkage tool),

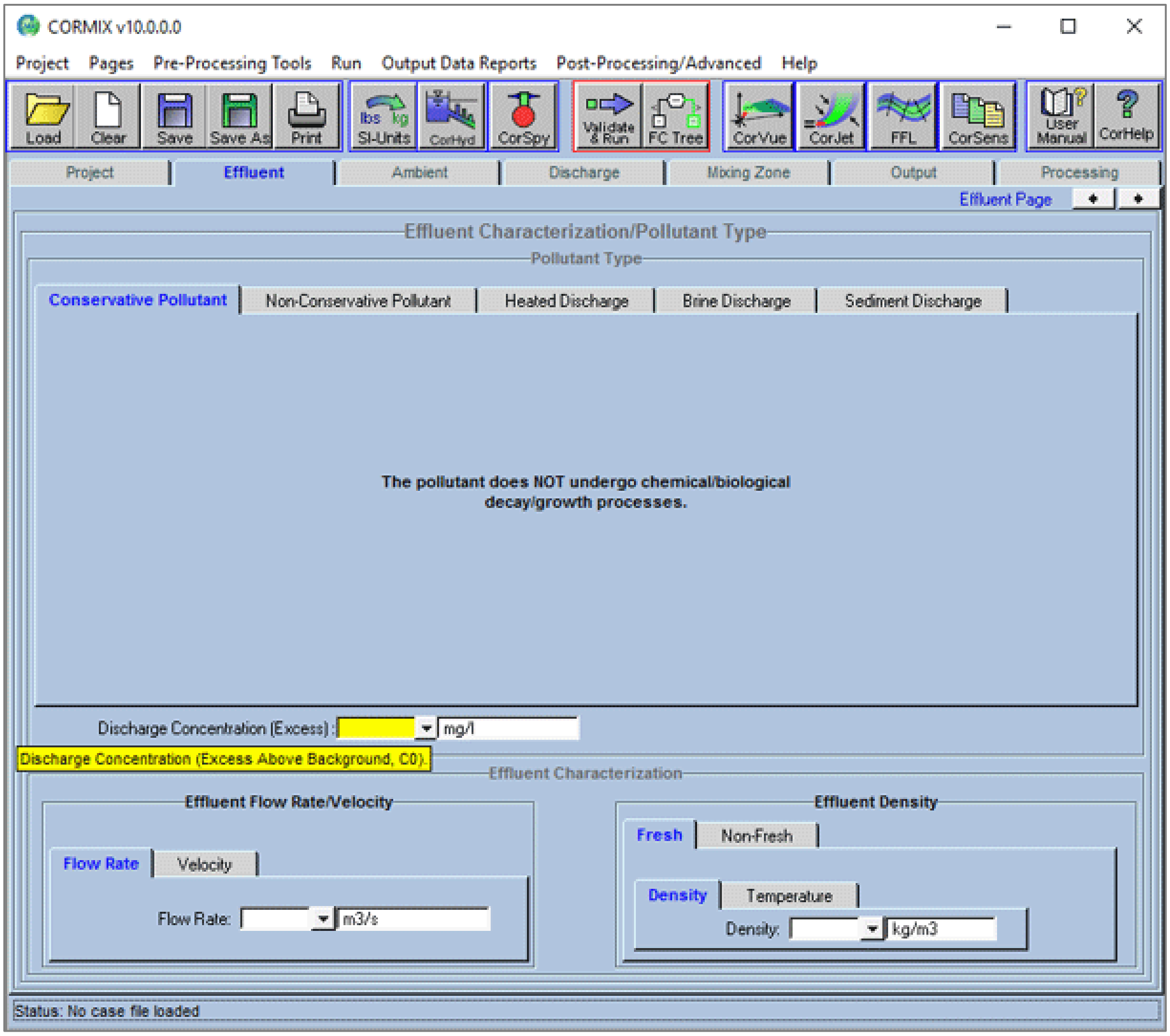
- CorHYD (an internal diffuser hydraulics design tool),
- CorSpy (an interactive 3-D outfall visualization tool),
- Far Field Locator (FFL; a tool that is used to reconcile CORMIX far-field plume predictions with field dye study data),
- CorVAL (a validation service to compare model results with a database of plume dilution experiment data),
- CorVue (an interactive 3-D plume visualization tool),
- CorSens (a batch processing tool used for conducting sensitivity studies),
- CorTime (an automated time series analysis tool for linking the CORMIX model to boundary conditions in far-field coastal circulation models), and
- CorUCS (a post-processing tool that converts outputs to WGS84 netCDF formats for import into ArcGIS and other mapping tools)

Data Needs/Model Input

At a minimum, CORMIX version 12.0 requires Windows 7/8/10, 250 MB of hard disk space, 1 GB RAM, and a broadband internet connection (MixZon, 2021; CORMIX, 2021f). CORMIX has a graphical user interface (GUI) that works in Windows operating systems (MixZon, 2021). The GUI prompts users to enter input data in a series of input data boxes. Figure 4-15 shows an example of the CORMIX GUI. The user can enter project information, input data, and select parameters for the output and processing in the GUI. Input data are categorized into four groups: effluent properties, ambient conditions, discharge conditions, and mixing zone properties (Doneker and Jirka, 2007). Table 4-9 provides a detailed list of inputs for each tab. Users have the option to include various levels of detail for model inputs. However, the model produces more accurate simulations with more detailed discharge and ambient flow characteristics, temperature characteristics, and receiving water geometries.

Effluent inputs: Effluent inputs include the flow rate or discharge velocity, the discharge concentration, the density and temperature if the effluent is saline, or only temperature if the effluent is freshwater (Doneker and Jirka, 2007; Morelissen et al., 2013).

Ambient inputs: The ambient conditions group requires several inputs. Geometric survey information and velocities for the receiving waterbody are needed at the discharge location and multiple cross sections throughout the mixing zone (Durkee, 2012). The receiving waterbody needs to be defined as bounded, if the waterbody is constrained by banks or beds, or unbounded, for instances where interaction with the far bank is not likely (Doneker and Jirka, 2007). For most mixing zone locations, ambient densities, temperature and the vertical distribution of density are also necessary (Durkee, 2012; Morelissen et al., 2013).



The pollutant does NOT undergo chemical/biological decay/growth processes.

Status: No case file loaded

Figure 4-15. The main screen for the CORMIX GUI.

The tabs that require input data are the Effluent, Ambient, Discharge, and Mixing Zone tabs. Each tab has a series of boxes (e.g., Design Case in the above screen shot) that prompt the user for input or information (CORMIX, 2021g).

Discharge inputs: The discharge inputs tab describes outfall design. The user should first select the appropriate subsystem (CORMIX1, CORMIX2, CORMIX3, or DHYDRO) for a single port, multiport, or buoyant surface discharge for the outfall design (Durkee, 2012). Data for nozzle orientation and diameter are also needed (Morelissen et al., 2013).

Mixing zone inputs: The user commands the number of output steps to display and the linear distance to model the mixing zone. The lines of output data do not affect the simulation accuracy, only the spatial resolution of simulation output.

Table 4-9. CORMIX Inputs

Input tabs	Input data
Effluent input	Pollutant type
	Conservative, non-conservative, heated, brine, or sediment
	Effluent Flow rate or velocity
	Effluent Density
	Effluent Temperature
Ambient input	Average Depth
	Depth at Discharge
	Wind Speed
	Bounded or Unbounded
	Steady or Unsteady
	Flowrate
	Velocity
	Manning’s n or Darcy-Weisbach’s friction factor f
	Freshwater or Non-Freshwater
	Uniform (Temperature and density)
	Stratified (Temperature and density)
Discharge input	Discharge geometry
	CORMIX1 (single port); CORMIX2 (multiport), CORMIX3 (surface)
	Distance to nearest bank
	Port diameter
	Height of port above bottom (for submerged outfalls)
	Height of port above center (for surface outfalls)
	Vertical angle of discharge
	Horizontal angle of discharge
Mixing zone input	Regulatory mixing zone
	Distance from the discharge location
	Cross sectional area of the plume
	Width of the effluent plume
	Region of interest
	Maximum analysis distance
	Grid intervals to define output detail

Model Outputs

CORMIX model outputs include plume centerline trajectory, velocity, dilutions, and plume width dimensions (Table 4-10) (Doneker and Jirka, 2007; Morelissen et al., 2013). Outputs can be modeled in 2-D or 3-D. CORMIX has graphical interface tools, such as CorVue, that depict the mixing zone characteristics and behavior in a variety of graphical visualizations (Doneker, 2014). These graphics can be saved in many formats, including jpeg, gif, bmp, and png, and the data can be exported in a comma separated value (.csv) format (Doneker, 2014). A graphics card is necessary to operate CorVue (Doneker and Jirka, 2007).

Table 4-10. CORMIX Output Variables. Additional output values and visualizations can be created using the CorSens and CorVal tools

Output
Plume centerline trajectory
Plume velocity
Plume dilutions
Plume width dimensions

Two additional tools, CorSens and CorVal, provide additional services that may be relevant to thermal mixing studies. In CorSens, discharge and ambient parameters can be varied, allowing the user to perform sensitivity analyses. These analyses provide additional information on how changing (or uncertainty in) parameter estimates affect mixing zone plume results (Doneker and Jirka, 2007). CorVal is a service that is provided by MixZon, available with a subscription, to validate CORMIX model prediction results (Doneker and Jirka, 2007).

4.4.2 Delft3D

Model Key Components and Processes

The Deltares User manual (Deltares, 2021b) provides information on model components and processes for Delft3D-FLOW (Table 4-11). Delft3D-FLOW is a finite difference model that can run simulations in 2-D and 3-D. Two grid systems are available for the horizontal plane, a rectilinear grid or a curvilinear grid. The vertical grid in 3-D simulations uses the σ coordinate system, in which vertical layers are curvilinear and sub-parallel to the boundaries of the waterbody, rather than being horizontal. Delft3D-FLOW has submodules that help generate model grids and boundary conditions, among other functions, for inputs to the simulation. Delft3D-FLOW does not have designated outfall submodules like those used in CORMIX; users need to generalize discharge inputs for thermal mixing simulations. Thermal simulations can incorporate unsteady conditions, such as changing or tidal flows, if needed.

Deltares has many modules in the Delft3D package (Deltares, 2021b):

- Deflt3D-WAVE (wave module),
- Deflt3D-FLOW (hydrodynamics module),
- Delft3D-WAQ (water quality module),
- Delft3D-MOR (morphology changes),

- Delft3D-PART (mid-field water quality and particle tracking module),
- Delft3D-ECO (ecological module), and
- Delft3D-SED (sediment transport module)

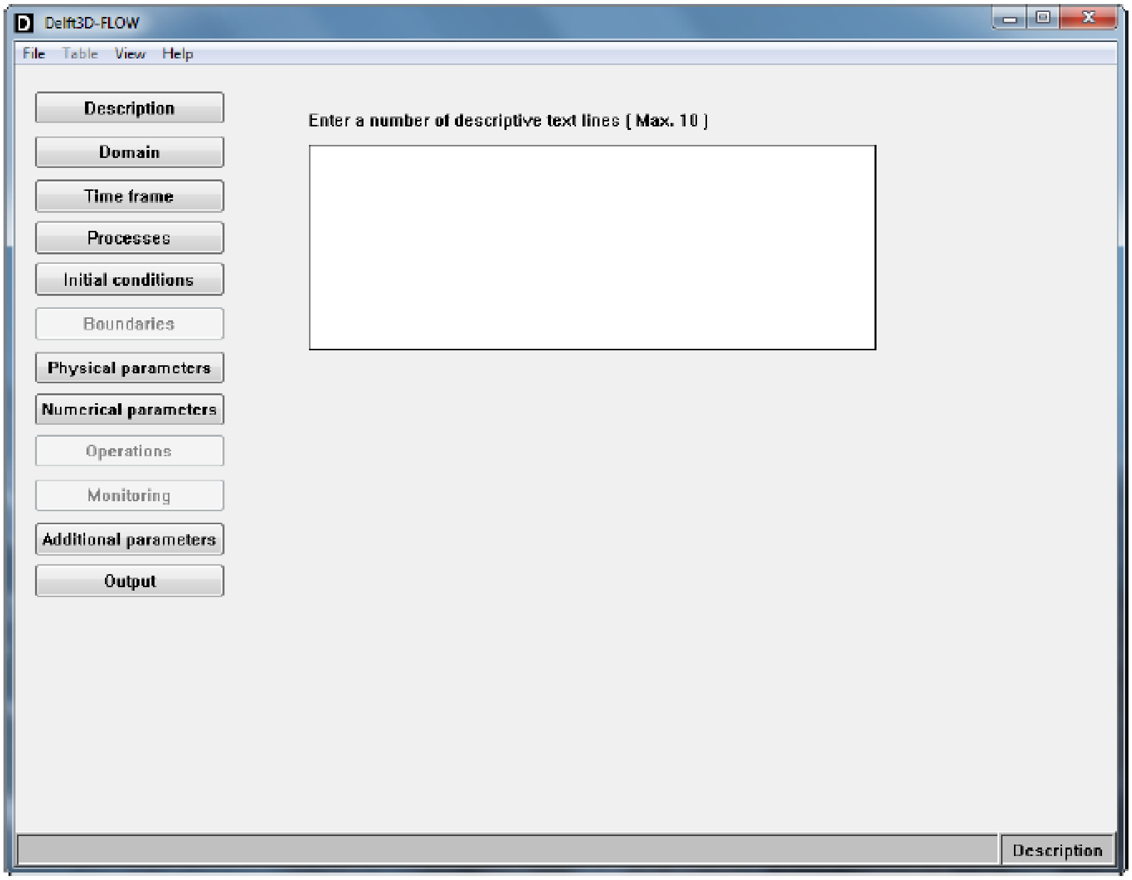
Deflt3D-FLOW is the hydrodynamic model that simulates thermal mixing in waterbodies (Morelissen et al., 2013). It can communicate with the other Deflt3D modules as necessary, for example a user may also need to include the wave module (Delft3D-WAVE) in coastal areas.

Table 4-11. Delft3D-FLOW Key Components and Processes

Key component/process	Delft3D-FLOW	References
Grid or coordinate system	Rectilinear and curvilinear (horizontal); σ coordinate (vertical)	Morelissen et al., 2013 Deltares, 2021b
Unsteady flow	Yes	
Boundary interactions	Yes (heat exchange through the free water surface, interaction with bed sheer stresses)	
Density currents	Yes - both temperature and salinity	
Dimensions	2-D and 3-D	
Time steps	User defined	
Outfall designs/discharge configurations	User defines the discharge or thermal input parameters	

Data Needs/Model Input

Delft3D can be run on MS Windows or Linux operating systems. To enter the Delft3D-FLOW module, the user selects the “Flow” button on the main menu in the Delft3D package. Users must create an input file called a Master Definition Flow file (MDF-file) in ASCII-file format (Deltares, 2021b). Deltares created a GUI to aid users in creating the MDF-file (Figure 4-16). The GUI contains several data groups; a data group is a set of related inputs to describe relevant characteristics, such as discharge. Table 4-12 provides descriptions for the input groups. There is also a visualization area window that shows a visual representation of gridded data contained in the MDF-file (Deltares, 20121b).



Source: Deltares, 2021b

Figure 4-16. Delft3D-FLOW GUI (Figure 3.7 in Deltares, 2021b).

Table 4-12. Input Groups for the Delft3D-FLOW Hydrodynamic Module

Inputs	Description
Domain	Contains sub-groups of grid parameters, bathymetry, dry points and thin dams.
Time frame	Set the time frame and time steps of the simulation. Contains the sub-groups of reference date, simulation start and stop time, time steps, and local time zone.
Processes	Define processes that affect the simulation. Inputs are dependent on the simulation. Examples include: temperature, salinity, wave, wind, and secondary flow.
Initial conditions	Set the initial values for the start of the computations for dependent variables that were defined in the processes portion of the setup.
Boundaries	Define all open boundaries locations, types and associated input data for the simulation.
Physical parameters	Set the physical conditions related to the processes addressed in the model. For example, the heat flux model should be included if temperature was selected as a process. Examples of other physical conditions are viscosity, roughness, and turbulence.
Operations	Select and define operations, such as point source discharge, into the model.
Additional parameters	Deltares provides add-ons, which can be selected as needed.

Model Outputs

Users can define what hydrodynamic outputs they want to include in simulation outputs (e.g., temperature, salinity, etc.). Delft3D-FLOW stores the output in four files: history file, map file, drogue file, and communication file. The files are described in Table 4-13. Deltares offers a general post processing program (GPP) that can reproduce or create plots from the simulation results (Deltares, 2021d; Deltares, 2021b). Outputs can be modeled in 2-D or 3-D. The data can be presented in graphical or tabular form, as well as animations (Deltares, 2021d).

Table 4-13. Output Files for Delft3D-FLOW

Output file	Description
History	Contains the quantities over the simulated time for specific points and cross-sections
Map	Contains the computed quantities for specified intervals for the simulation area
Drogue	Contains the coordinate positions for each time step
Communication	Contains the results that are needed as inputs to other modules

Source: Deltares, 2021b

4.4.3 Environment Fluid Dynamics Code (EFDC)

Model Key Components and Processes

EFDC is a finite difference model and can be run in 1-D, 2-D, or 3-D modes (Shoemaker et al., 2005; Hodge et al., 2011). The horizontal coordinate system can be either cartesian or curvilinear. Cell size is defined by the user and can be changed along the length of the plume or simulation to add more or less resolution as needed (Hodge et al., 2011). EFDC offers a bottom boundary layer submodule to account for wave and current interaction (Hamrick, 2007a). Table 4-14 provides a summary of EFDC components and processes.

Table 4-14. EFDC Key Components and Processes

Key component/process	EFDC	References
Grid or coordinate system	Cartesian or curvilinear (horizontal); σ (vertical) coordinate	Shoemaker et al., 2005 Hamrick, 2007a U.S. EPA, 2007
Unsteady flow	Yes	
Boundary interactions	Yes	
Dimensions	1-D, 2-D, 3-D	
Time steps	User defined	
Outfall designs/discharge configurations	User defined	

Data Needs/Model Input

The EFDC model was written in FORTRAN 77 and can be run on the following Windows operating systems: 95, 98, NT, 2000, and XP (U.S. EPA, 2015). Currently the input system has an interactive user manual with documentation for creating inputs (variables, files, and formatting). The software includes preprocessor tools for grid generations and model initialization. In addition, a variety of extensions and data processing tools which build upon the EPA-distributed EFDC software have been developed by third parties and are available for free download and for purchase (EE Modeling System, 2021). Table 4-15 provides a list of input groups that are needed to run EFDC.

Table 4-15. EFDC Inputs

Inputs
Horizontal grid specification
General data and run control
Initialization
Physical process specification
Time series forcing and boundary conditions

Source: Hamrick, 2007a.

Model Outputs

EFDC includes utilities for viewing and post-processing data, including MOVEM graphical post-processor. Data output from EFDC can also be saved in a variety of formats for post-processing in other graphics packages such as IDI, TECPLOT, and MATLAB (U.S. EPA, 2007). Table 4-16 lists EFDC model output files.

Table 4-16. EFDC Outputs

Output files
Diagnostic files
Restart and transport field files
Time series, point samples and least squares harmonic analysis files
2-D graphics and visualization files
3-D graphics and visualization files

Source: U.S. EPA, 2007b.

4.4.4 MIKE 3 FM

Model Key Components and Processes

The MIKE 3 FM system uses a flexible mesh for structuring the simulation of the receiving water. The flexible mesh simulation engine uses finite volume methods and an unstructured grid system so it can model more complex and stratified environments. For the flexible mesh simulation, triangles of varying size are used to define or describe the horizontal plane.

MIKE 3 FM has many modules that can each be bought individually depending on the modeling needs. At least one module is relevant for thermal modeling: the MIKE ECO Lab module for simulating ecological systems in the aquatic environment (DHI, 2020). Table 4-17 provides a summary of the model key components and processes.

Data Needs/Model Input

MIKE 3 FM can be run in Linux, Windows 10 (64-bit version), and DHI provides cloud-based software access via Microsoft's Azure cloud-hosing service. It requires a minimum of 40 GB of hard disk space (DHI, 2020). The MIKE 3 GUI has a navigation tree to show each section of the setup files, an editor window to select and define inputs, and a validation window to show validation errors as the user sets inputs (DHI, 2021a).

Table 4-17. MIKE 3 Key Components and Processes

Key component/process	MIKE 3 FM	References
Grid or coordinate system	Varies depending on the simulation engine selected (single, multiple, or flexible mesh)	DHI, 2021a
Unsteady state	Yes	
Boundary interactions	Yes	
Density currents	Yes	
Dimensions	3-D	
Time steps	Defined by user	
Unstratified vs. stratified ambient	Stratified	

Inputs are listed and described in Table 4-18. Inputs vary slightly for each grid system and additional inputs may be needed depending on the modules selected by the user. The inputs presented in Table 4-18 are relevant to thermal modeling within the MIKE 3 framework (DHI, 2021a). For all MIKE 3 models, the user defines the grid and bathymetry over which computations will occur (Moharir et al., 2014). The user also defines the time steps and the duration of the simulation. Either water surface level or velocity need to be defined for initial conditions. Boundary condition and source/sink inputs can be entered as constants or they can vary over the duration of the simulation as defined by the user. If wind is included as a variable, the user can keep it constant throughout the simulation or vary it over time and space. Some inputs listed in Table 4-18 are not necessary for every module and have been identified accordingly. DHI has additional packages to aid in acquiring or defining model inputs (DHI, 2021a).

Table 4-18. Inputs for MIKE 3 FLOW FM

Inputs	Description
Domain and time	Computational mesh or grid and bathymetry; Simulation length and time step
Initial conditions	Water surface level and velocity
Boundary conditions	One or more of the following: flow boundary, water surface level, velocity profile
Physical conditions	Bed resistance and turbulence
Wind	Speed, direction, and friction factors
Sources and sinks	Location and magnitude of point source discharge or sinks
Temperature and salinity	Initial and boundary conditions, point sources, and heat exchange (e.g., air temperature or relative humidity)
Other potential inputs	Precipitation, ice cover, wave radiation stresses

Model Outputs

MIKE 3 FM provides output values on the flexible model grid and data can be reviewed using the Data Viewer, which is included in the basic MIKE 3 module (MIKE, 2020). Specific output variables are listed in Table 4-19. MIKE Zero is an additional module that allows the user to view output variables in 2-D or 3-D color presentations, in many time steps, and at different spatial locations. MIKE Zero also outputs discharge calculations, statistical calculations of parameters, and digital video animations (DHI, 2021a).

Table 4-19. Output Variables for MIKE 3 FLOW FM

Outputs
Basic variables
Water depth/surface elevation
Flux densities
Velocities
Density, temperature, and salinity
Additional optional outputs
Current speed and direction
Wind velocity
Air pressure
Drag coefficient
Precipitation
Evaporation
Turbulence

Source: DHI, 2021a.

4.4.5 CE-QUAL-W2

Model Key Components and Processes

CE-QUAL-W2 is a finite difference model that has been successfully applied to thermal mixing in complex waterbodies (Shoemaker et al., 2005; Wells, 2021). The model uses a variable grid system so it can be applied to geometrically complex waterbodies, including branching waterbodies. The user can define outfall designs and dimensions as part of the input files (Wells, 2021). Turbulence is modeled using eddy coefficients (Irvine et al., 2005). A 3-D particle tracking algorithm is included which models movement of particles due to turbulence and advection (Wells, 2021). Boundary conditions can be varied over time within simulations (Wells, 2021). Multiple waterbody cascade modeling can be performed where flow passes sequentially through multiple waterbodies (Wells, 2021). Table 4-20 provides a summary of model key components.

Table 4-20. CE-QUAL-W2 Key Components and Processes

Key component/process	CE-QUAL-W2	References
Grid or coordinate system	Variable, user defined	Shoemaker et al., 2005 Wells, 2021
Unsteady state	Yes	
Boundary interactions	Yes	
Dimensions	2-D	
Time steps	User defined	
Unstratified vs stratified ambient	Both	
Outfall designs/discharge configurations	Dimensions and physical parameters defined by the user	

Data Needs/Model Input

CE-QUAL-W2 runs in both 32 and 64-bit versions of Windows operating systems. Inputs for CE-QUAL-W2 can be added using a text editor, a spreadsheet editor, or using the GUI. The GUI helps users edit or adjust files, but input files are primarily created using spreadsheet software or text editors (Wells, 2021). Bathymetry files can be generated within the GUI using x/y/z topographic maps (Wells, 2021). Portland State University maintains an Excel macro utility that can help users create input files for CE-QUAL-W2 (Wells, 2021). The GUI and Excel macro are both included within the files downloaded for the CE-QUAL-W2 model.

Model inputs, listed in Table 4-21, are divided into six groups: geometric data, initial conditions, boundary conditions, hydraulic parameters, kinetic parameters, and calibration data. The following input descriptions are from Wells (2021):

- **Geometric data:** Specific geometric data are needed (see Table 4-21 for a list) in order to create the grid system for the model.
- **Initial conditions:** Waterbody type, time (start and end), and temperature conditions are all required inputs. Users can choose to include information for inflows, outflows, and ice thickness if desired.
- **Boundary conditions:** Surface boundary conditions (see Table 4-21 for a list) are required for each simulation, however head boundary conditions are not. Certain types of inflows and outflows (listed in Table 4-21) are recognized within the modeling system and can be incorporated and defined as needed in the simulation.
- **Hydraulic parameters:** Dispersion and diffusion coefficients for temperature are specified in the control file. Bottom friction can be defined using the Chezy coefficient or Manning’s n.
- **Kinetic parameters:** Most of the parameters pertain to water quality variables, so these inputs are optional. CE-QUAL-W2 provides a list of coefficient values in Appendix C of the user manual.
- **Calibration data:** Data used to provide initial and boundary conditions and to validate model output for calibration purposes.

Table 4-21. CE-QUAL-W2 Inputs

Input tabs	Input data
Geometric data	Computational grid
	Longitudinal spacing, vertical spacing, average cross-sectional width, waterbody slope
	Bathymetric data
	Grid cell types
	Boundary cells
	Branches
Initial conditions	Time
	Temperature
	Inflow/outflow
	Restart
	Waterbody type
	Ice thickness
Boundary conditions	Inflows
	Upstream inflows, tributary inflows, distributed tributary inflows, precipitation, internal inflows
	Outflows
	Downstream outflows, lateral withdrawals, evaporation, internal outflows
	Head boundary conditions
	Surface boundary conditions
	Surface heat exchange, solar radiation absorption, wind stress, gas exchange
Hydraulic parameters	Dispersion/diffusion coefficients
	Bottom friction
Kinetic parameters	Model options to include kinetic fluxes and coefficients for simulating water quality factors for over 120 parameters, such as algae, epiphyton, nitrogen, phosphorus, organic matter, and dissolved silica
Calibration data	In-pool
	Time-varying boundary conditions

Source: Wells, 2021; Shoemaker, *et al.*, 2005.

Model Outputs

CE-QUAL-W2 has a post processor called W2Tools.[30] W2Tools provides model calibration and data visualization for model results (DSI, 2012). Table 4-22 summarizes the CE-QUAL-W2 model outputs.

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[30] Previous versions of this software released the post processor under the name W2-Post.

Table 4-22. CE-QUAL-W2 Model Outputs

Output files
Profile/snapshot
Time parameters
Meteorological parameters
Inflow/outflow parameters
Balances (volume, thermal, or constituent mass balance)
Geometry
Water Surface
Temperature/Water quality
Time series
Contour plot
Vector plot
Spreadsheet

Source: DSI, 2012.

5.0 Case Studies

This section provides an overview of several examples of high-quality 316(a) documents that illustrate the types of analyses and information needed, as well as suggested information or analyses that can be included in an assessment of thermal discharges.

5.1 Introduction

EPA is interested in assessing existing Section 316(a) demonstrations and thermal mixing zone studies to identify and update best practices with a long-term goal of improving guidance for conducting such studies. EPA reviewed 37 thermal mixing studies obtained from various sources. This review indicates that many 316(a) demonstrations or thermal mixing zone studies date from the 1970s and 1980s. The applicability and conclusions of these studies are unlikely to reflect current receiving water conditions due to changes in river hydrology, water quality, watershed land use, and indigenous and/or sensitive biological receptors. In these cases, the permitting authority should work with the permittee prior to reissuance to ensure adequate information is available to support the thermal mixing zone request or 316(a) alternate limitation request.

Section 5.2 describes how EPA identified good examples of well-designed studies and describes six studies in detail (out of 37 facilities reviewed) in Section 5.3 below. Each study reflects the site-specific facility discharge and environmental setting, but together they provide examples of desirable study scope and features to help guide and inform the design and planning of future thermal mixing studies, such as identifying design elements and data collection priorities that permit writers should consider when reviewing study work plans. Section 5.4 provides information on desirable elements of a thermal study.

5.2 Review and Selection of Case Studies

EPA obtained information and documentation of Section 316(a) demonstrations and thermal mixing studies (5.2.1). Section 316(a) demonstrations were conducted at 19 facilities while thermal mixing or plume studies alone were sufficient to address thermal issues at another 18 facilities. From these 37 studies and using the criteria described in Section 5.2.2, EPA selected six examples for further evaluation.

5.2.1 Sources of Thermal Mixing Studies

EPA headquarters and Regions provided electronic copies of Section 316(a) demonstrations and supporting thermal mixing studies. EPA also identified additonal studies and information in data compiled for previous projects (e.g., the 316(b) rulemaking record) and through Internet searches. EPA collected information about each plant's monitoring requirements from final or draft NPDES permits, or in cases where EPA was unable to find the permits online, from EPA's Enforcement and Compliance History Online (ECHO) database and the Integrated Compliance Information System (ICIS) database in Envirofacts.

EPA obtained thermal studies conducted at 37 facilities. For each facility, EPA considered:

- Geographic information (i.e., city, state, EPA region),
- NPDES permit information (permit discharge, receiving water, temperature effluent limitations), and

- Thermal study information (types of studies, dates of completion, types of thermal models used, and additional details).

The set of studies contains four examples from Region 1; one example each for Regions 2, 3, and 4; 25 examples from Region 5; and five examples from Region 7. The majority of facilities discharge to freshwater rivers. The completion dates of these studies range from some of the earliest permits issued under the CWA to the present day: 1977-79 (10 studies); 1980-89 (3 studies); 1990-99 (2 studies); 2000-09 (17 studies); and 2010-present (5 studies). A variety of computational methods and thermal mixing models were used. The CORMIX, alone or with an accompanying far-field model, was the most common model and used in 13 applications.

5.2.2 *Selection of Case Studies*

EPA selected case studies for this document based on the following characteristics:

1. **Study date** – Due to improvement in thermal data collection and management and applications of thermal modeling and monitoring tools, recent studies are more informative. For this criterion, EPA considered only studies completed later than 2000.
2. **Scope of study** – Studies with more complex or extensive modeling or field monitoring requirements were preferred over simple, mass-balance models using temperature surrogates (e.g., British thermal units [BTUs]).
3. **Supporting documents** – Studies with additional supporting documents (e.g., permit fact sheet, ecological surveys, or detailed description of the model) were preferred.
4. **Environmental settings** – EPA selected studies that covered a range of environmental settings including coastal marine, estuary, coastal freshwater, as well as large rivers and small stream. Where possible, EPA attempted to select examples from different EPA regions.

Based on these criteria, EPA selected six examples for case studies. A brief description and rationale for selection are provided in Table 5-1.

Table 5-1. Selected Case Studies

Facility Name	Location	EPA Region	Study Summary
BP Whiting Refinery	Whiting, IN	5	The thermal study was conducted in 2011 using a combination of CORMIX and EFDC models and the Section 316(a) demonstration report was submitted in 2012. The receiving water is freshwater coastal (Lake Michigan).
Brayton Point	Somerset, MA	1	A Section 316(a) demonstration was completed in 2001 and thermal study in 2002 using a combination of CORMIX and Water Quality Modeling and Analysis Program (WQMAP) models. This facility has an extensive regulatory history due to challenges by the permittee and has since closed. The receiving water is Mount Hope Bay, an enclosed marine coastal embayment.
Quad Cities Nuclear Station	Cordova, IL	5	The thermal study was conducted in 2004 using the 3-D computational fluid dynamics (CFD) model and the Section 316(a) demonstration report was submitted in 2009. The receiving water is freshwater river (Mississippi River).

Facility Name	Location	EPA Region	Study Summary
Saint Joseph Energy Center	New Carlisle, IN	5	A thermal evaluation was conducted to establish ATELs[31] for a power plant to be constructed. While the discharge is a relatively minor amount of "cooling water blowdown," the discharge will convert a small ephemeral ditch (receiving water) into a perennial stream.
Valley Power Plant (VAPP)	Milwaukee, WI	5	A Section 316(a) demonstration was completed in 2012 using the Estuarine and Coastal Ocean Model (ECOMSED) as the thermal model. The receiving water is a freshwater river near its confluence with Lake Michigan (i.e., Milwaukee Harbor Estuary).
Vermont Yankee Nuclear Power Station	Vernon, CT	1	A Section 316(a) demonstration report was conducted in 2004, using a 3-D, time-varying hydrothermal model (BFHYDRO) and analyzing a 30+ year biological database for statistically significant trends. The receiving water is a freshwater river (Connecticut River).

5.3 Case Study Facilities

This section provides a detailed summary of the thermal study at the six selected facilities.

5.3.1 BP Whiting Refinery

The BP Whiting Refinery is located on the southern shoreline of Lake Michigan between Calumet and Indiana Harbors, Indiana. The facility conducted a Phase I Thermal Plume Study and a Phase II Thermal Variance Study as part of the request by BP for renewal of the permit's existing ATEL.

Facility Characteristics and Environmental Setting

Plant Description

BP Products North America Inc. owns and operates a petroleum refinery (i.e., BP Whiting or the "Refinery") located on approximately 1,400 acres within the boundaries of Whiting, East Chicago, and Hammond, Indiana, near the southern tip of Lake Michigan. The facility (NPDES permit No. IN0000108) is classified under Standard Industrial Classification (SIC) Code 2911 Petroleum Refinery. It produces a variety of petroleum products, including gasoline of all grades, diesel fuel, heating fuel, jet fuel, asphalt, petroleum coke and petroleum intermediates (IDEM, 2013).

BP Whiting uses OTCW drawn from two intakes located approximately 1,200 feet offshore in Lake Michigan and returned through a discharge outfall (002) structure consisting of an overflow weir, discharging over riprap to the surface of a small bay in Lake Michigan (EA, 2012). The cooling water discharge has a long-term average of 73.7 MGD with a permitted maximum monthly average of 86.2 MGD (IDEM, 2013).

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[31] Some states refer to NPDES permit thermal variances as "alternative effluent limitations," while others use the term "alternative thermal effluent limitation" (ATEL). For consistency and clarification, this document uses the term ATEL throughout.

Environmental Setting

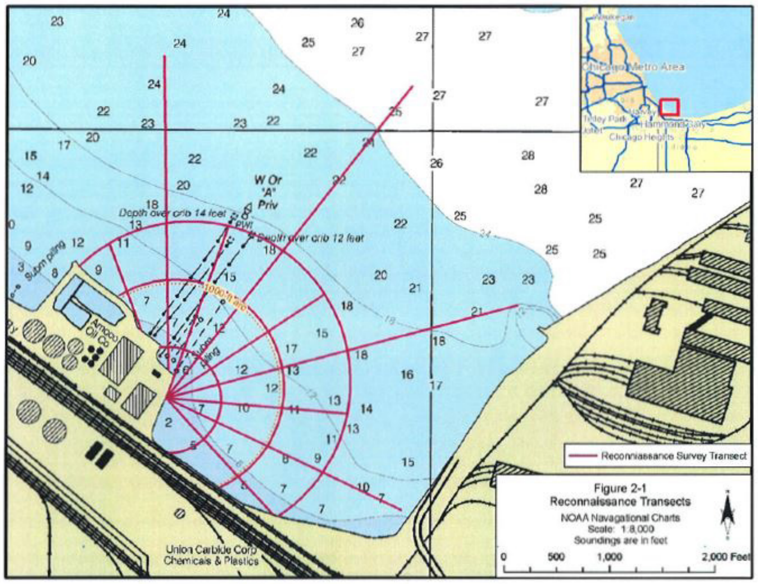

Figure 5-1. Local harbor near BP Whiting Refinery showing Field Reconnaissance transect lines.

The receiving waters for the BP Whiting thermal discharge is Lake Michigan (Figure 5-1). The lake is designated as an outstanding state resource water, to be maintained and protected in its present high quality without degradation in accordance with state regulations.[32] Lake Michigan is designated for full-body contact recreation and capable of supporting a well-balanced warm water aquatic community. The Indiana portion of the open waters of Lake Michigan is designated as salmonid waters meaning that water quality must be capable of supporting a salmonid fishery.

In the southwestern portion of the lake near the Refinery, currents are predominantly affected by the overall circulation patterns in the lake (EA, 2012). Close to shore, convection, shore-normal pressure gradient and shoreline orientation and features will affect currents. Vertical temperature stratification is rarely observable in the shallower water, if present at all, and is not maintained for long periods. The thermal discharge is well protected by the Calumet Harbor breakwater and the Indiana Harbor complex, which may affect longshore currents. Near-shore currents mainly follow the general direction of the wind, and in the instance of the wind blowing toward the shore, the lake water will deflect to follow the shoreline. Near the Refinery, the most common and strongest currents have been found to be towards the east and east-southeast.

RIS

Because there were no site-specific biological data collected in conjunction with the previous Section 316(a) demonstration, a field study was conducted to characterize the local fishery and identify candidate RIS. BP conducted fishing surveys using electrofishing (in 4 zones), gillnetting (in 9 locations), and trawling (in 9 locations). Surveys were conducted in July, August-September, and October 2011. Locations included six within the expected thermal plume and three acting as near-shore or off-shore controls (EA, 2012). The 2011 fishery surveys collected 32 species. Forage species (sand shiner, alewife, spottail shiner, and round goby) dominated numerically but, by weight, the catch was dominated by common carp, freshwater drum, Chinook salmon, walleye, channel catfish, and gizzard shad (EA, 2012).

The macrohabitat within the four electrofishing zones were evaluated using the Qualitative Habitat Evaluation Index (QHEI) developed for Lake Erie (Ohio EPA, 2010). The five principal components of QHEI

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[32] Lake Michigan is protected by Indiana rules governing WQS for the Great Lakes Basin and as such, it is subject to the WQS specific to Great Lakes system dischargers as found in 327 IAC 2-1.5, 327 IAC 5-1.5, and 327 IAC 5-2.

are substrate, cover type, shoreline morphology, riparian zone and band erosion, and aquatic vegetation quality.

Six fish species[33] were approved by the IDEM. All RIS selected were known to occur near the discharge point (EA, 2012). These six RIS were used to evaluate the model-predicted worst-case absolute temperature, given both high ambient temperatures and the maximum permitted thermal loading from the refinery.

Section 316(a) Compliance History

Previous studies conducted to demonstrate compliance with Section 316(a) for facility thermal limitations (CWA Section 316(a)) and the applicable thermal standards are described below.

Previous Studies

A CWA Section 316(a) thermal demonstration study was jointly conducted by Union Carbide Corporation and BP (formerly Amoco Oil Corporation) and approved by EPA in 1975 (EPA, 1975). The study included plume mapping data collected in 1971-1973 and biological data collected from several power plants in the southern portion of the lake during the same time frame (Limnetics, 1975). The study concluded that the thermal effluents from the Refinery were not expected to appreciably harm the indigenous population of fish, shellfish, and associated wildlife.

Based on that study, the state of Indiana established ATELs; these limits were retained through several permitting cycles. However, the 2007 NPDES permit stipulated that an updated Section 316(a) variance request be prepared with the 2012 permit renewal application.

Thermal Effluent Limitations

The permitted monthly average daily heat load limit for BP Whiting is 1.7×10^9 BTUs per hour (BTU/hr) and a daily maximum heat load limit of 2.0×10^9 BTU/hr. The permittee must demonstrate that these thermal inputs comply with applicable state standards. According to Indiana water temperature criteria for Lake Michigan, the receiving water temperature cannot be more than 3°F (1.7°C) greater than existing background temperature at a maximum distance of a 1,000-ft arc (i.e., edge of mixing zone) inscribed from the thermal discharge. In addition, the receiving water temperature outside of the 1,000-ft arc cannot exceed specified monthly temperatures in Lake Michigan,[34] except when an exceedance can be demonstrated to be caused by the ambient water temperature at the intake. Typically, summertime criteria (80°F [26.7°C] from July through September) are the most difficult to achieve at most thermal effluents. The 2010 thermal study was conducted to determine whether both the 3°F (1.7°C) change from ambient temperature and absolute temperature criteria would be met.

Thermal Plume Study

As noted above, re-application for the 2012 permit required the preparation of an updated 316(a) variance request. Accordingly, BP prepared a Whiting Refinery Effluent Thermal Study Plan for fulfilling the thermal plume and Section 316(a) variance studies and submitted the Plan to IDEM in July 2010. The

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[33] Alewife (*Alosa pseudoharengus*), Chinook salmon (*Oncorhynchus tshawytscha*), common carp (*Cyprinus carpio*), spottail shiner (*Notropis hudsonis*), smallmouth bass (*Micropterus dolomieu*), and yellow perch (*Perca flavescens*).

[34] Monthly maxima are listed in 327 IAC 2-1.5(8).

Plan proposed a phased approach with Phase 1 consisting of a thermal plume study and Phase 2 providing a Section 316(a) demonstration study, if indicated by the plume study. IDEM approved this approach.

In Phase 1, BP conducted a four-week field survey in the receiving waters near the cooling water discharge from September 23 to October 27, 2010. The survey included the deployment of 13 thermistor array moorings to collect temperature data and two acoustic doppler current profilers to collect current data. Prior to mooring deployment, a boat-based reconnaissance survey was conducted to characterize the mooring locations and depth, and the extent of the thermal plume. A similar survey was also conducted following the deployment and prior to retrieval, to provide additional characterization of temperature data at multiple locations and verify thermistor data (EA, 2012).

The CORMIX model was used as a screening level tool to determine the size of the model domain necessary to fully capture the thermal plume. Based on the CORMIX results, it was determined that the appropriate model domain extended approximately 3 miles from the discharge location (AECOM, 2011).

Accordingly, BP selected the EFDC model to develop the thermal model. EFDC was considered appropriate due to the complex hydrodynamics of the BP Whiting thermal discharge, the characteristics of the plume, and the need to evaluate the thermal plume in three dimensions. The EFDC model was calibrated using the first two weeks of field survey data (9/27-10/11/2010). The calibrated model was then validated using the second two weeks of field survey data (10/11-25/2010). Comparison of predicted data and observed data from the validation period indicated that the model calibration performed satisfactorily and IDEM accepted the model as providing a reasonable representation of the thermal plume.

The calibrated and validated model was used to predict the extent of the thermal plume under a range of “worst-case” heat dissipation scenarios. These scenarios assumed the maximum permitted monthly discharge under existing and proposed operations (discharge expected to decrease in future) under both spring and summer ambient conditions and with varying wind direction and nearshore current direction combinations. The results of model scenario runs indicated that the thermal plume extended beyond the 1,000-ft arc encircling the outfall under worst-case scenarios. The proposed future plant conditions were not expected to have any significant impacts on the extent of the thermal plume. The extent of the thermal plume varied depending on wind and local currents. Under all modeled scenarios, the maximum ΔT was 18°F (10°C), although the size of the area encompassed by the 18°F (10°C) contour was relatively small. The results of the thermal plume study indicated that Phase II would be required for the full demonstration.

Section 316(a) Demonstration

EPA's draft guidance on implementation of Section 316(a) allows for three types of demonstrations.[35] BP proposed a “Type III” or hybrid approach in which a study plan is specifically developed for the facility

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[35] *Type I Demonstration* - a demonstration based on field studies conducted to demonstrate the “absence of prior appreciable harm” to the BIC from a discharge. Type I Demonstrations can be used by existing dischargers (U.S. EPA, 1977). *Type II Demonstration* - a predictive demonstration based on literature, lab, and field studies conducted to assure that proposed ATEL will provide adequate protection and propagation of RIS despite previous harm or lack of historical data. Type II Demonstrations can be used by new discharger or existing dischargers

being considered (IDEM, 2015). The hybrid approach is typically used when older studies need to be updated or an existing facility is expanded. BP choose a Type III Demonstration in an attempt to show that there had been no prior appreciable harm due to prior operation and that the agreed upon group of RIS would be protected under continued operations of the refinery.

As part of the IDEM-approved workplan, site-specific fish data were collected to determine whether a BIC is present in the vicinity of the BP Whiting thermal outfall and, therefore, whether the proposed ATEL was justified. As described above, fish were sampled by gillnetting and trawling at nine locations and by electrofishing at four zones. Sampling areas were selected based on modeling results that predicted plume temperatures and positions under various current and wind scenarios.

The biothermal assessment was based on the 2011 sampling results for 14 biological metrics. The comparison of biological metrics evaluated fish populations within the thermally affected areas relative to those in control areas. Habitat assessment results indicated fair to poor habitat at all locations, which were characterized by sand substrate, poor riparian quality, and no aquatic macrophytes. Comparison of the fishery resources within and outside of the plume indicated no statistical difference nor were there difference in macro-habitat in these areas.

A worst-case analysis compared literature values on thermal tolerances of the six RIS to the model-predicted worst-case absolute temperature given both high ambient temperatures and the maximum permitted thermal loading from the refinery. The worst-case analysis for the six RIS indicated that during the summer, upper thermal tolerance values of the cool and cold water species (i.e., alewife, yellow perch, and Chinook salmon) would be exceeded in portions of the thermal plume. However, except during the winter, the plume would mainly be at the surface. Thus, BP noted that, except in the winter, these species could avoid the plume by swimming either under or around it. BP further noted that the natural offshore movements of some species during the summer and fall, particularly Chinook salmon, would further limit contact with the plume.

BP concluded that there has been no "prior appreciable harm" as defined in Section 316(a), and that the BIC would be protected in the future even under worst-case conditions. BP based these conclusions on a lack of site-specific effects on the fish species in and outside of the plume area and the worst-case RIS analysis.

Assessment

IDEM received the NPDES re-application from BP in July 2012 for renewal of the existing ATEL. IDEM reviewed the results of the Thermal Impact Study. Based on the site-specific data showing no demonstrated effect on the fish community near the refinery and the worst-case analysis predicting no effects to RIS, IDEM allowed BP Products North America to continue using the existing ATEL because IDEM believes that the alternate effluent limitations will ensure the protection and propagation of the balanced and indigenous population of fish, shellfish, and wildlife in and on the waterbody.

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applying for an ATEL. *Type III Demonstration* - a demonstration that is conducted to address low potential impact discharges or when a custom study is necessary to ensure the BIC would be protected. These studies incorporate many of the features of a Type I and Type II Demonstration. Essentially, this is a term for any demonstration type agreed to by the NPDES discharger and the permitting authority that would not strictly adhere to the protocols established in this guidance for a Type I or II Demonstration (IDEM, 2015).

Strengths

- Used non-proprietary model (EFDC) as recommended by EPA (2009).
- Modeling assessment included worst-case scenario under adverse lake conditions at maximum power output.
- Did macro-habitat evaluation as well as fishery surveys.
- Conducted ecological surveys in numerous areas with both near-shore and off-shore controls.
- Documented location and justification of array moorings both before and after surveys. Verified the accuracy of thermistors with boat-based surveys.

Weaknesses or Areas for Improvement

- Calibration and verification of model were based on two weeks data which may not be representative of variability of long-term climatic conditions.
- Spring and summer conditions were represented by range of meteorological conditions on a single day in April or August which may not be representative variability of long-term climatic conditions.
- No comparison to 2011 survey results conducted due to lack of prior ecological data.
- Used a limited number of RIS considering only finfish community.
- Demonstrated potential impacts during spring and summer but did not quantify effects or potential behavioral mitigation.
- Focused on exceedance of acute thermal limits in RIS with little evaluation of chronic effects.
- Did not explicitly consider impacts of climate change.

BP Whiting Refinery Case Study References

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5.3.2 Brayton Point Station

The Brayton Point Station (BPS or the "Station") is a power plant located in Somerset, Massachusetts, that used coal, natural gas, and oil as fuel sources. Starting operations in the early 1960s, the power station was one of the largest in New England. Renewal of the permit in 1998 with previously existing effluent thermal limitations was controversial and led to intensive negotiations between the regulatory agencies, the permittee, and environmental organizations. Accordingly, BPS was the subject of an unusually comprehensive Section 316(a) Demonstration that culminated in 2002 permit modifications that reflected the proposed conversion of the plant from OTCW to a closed cycle system. BPS changed ownership several times following the issuance of the 2002 permit. In September 2013, the new owners announced that the plant would be shut down in May 2017, citing low electricity prices as well as high costs to meet environmental standards and maintain aging facilities.

Facility Characteristics and Environmental Setting

Plant Description

The BPS (NPDES Permit No. MA0003654) site covers approximately 250 acres at the confluence of the Taunton and Lee Rivers. Four fossil-fueled electric power generating units are contained in boiler and turbine houses, which are connected in line to form the power plant. The electrical generating capacities of these units are: Unit 1, 250 MW; Unit 2, 250 MW; Unit 3, 375 MW; and Unit 4, 450 MW (EPA, 2002a). At the generating peak in the 1990s, the once-through condenser cooling system flow for Units 1–3 plus service water was 966 MGD. Unit 4, which was originally designed for closed-cycle, was converted to once-through operation in 1984 with a design flow of approximately 395 MGD. The Station draws water for cooling purposes from Mount Hope Bay (MHB or "the Bay") at the Taunton and Lee Rivers, and discharges the water through a 3,200-foot long discharge channel to upper MHB. The surface discharge structure includes a Venturi portal at its mouth to increase exit velocities into the Bay. The outfall generates a discharge jet, which enhances mixing and dissipation of momentum relatively close to the outfall. During the 1990s, the Station discharged a maximum of 1,300 MGD of heated effluent when its four generating units are in operation (Swanson et al., 2006).

Environmental Setting

The receiving water is MHB, a shallow estuary seven miles in length along a north-south axis with a surface area of 13.6 square miles (mi^2) and a volume of 53 billion gallons at mean low water (Chinman and Nixon, 1985). MHB is located in the states of Rhode Island and Massachusetts and is relatively enclosed but is connected to Narragansett Bay by the Narragansett Bay East Passage and the Sakonnet River (Figure 5-2). MHB is generally shallow with an average depth of 18.7 ft (Chinman and Nixon, 1985).

Water circulation in MHB is primarily influenced by tidal flow, wind, and freshwater flow. Five rivers flow into the Bay: Taunton, Cole, Lee, Kickamuit, and Quequechen. Of these, the Taunton River is the most important tributary with an average flow of 7,846 gallons/seconds (exceeds the combined flow of the other four rivers) (EPA, 2002b). Tides are the primary driver of internal circulation in MHB with 7.9 billion gallons of water being flushed through the bay twice a day. Tidal currents are generally between 0.3-0.8 cfs with a mean tidal range of 4.4 ft (Spaulding and White, 1990; cited in EPA, 2002b). Currents are important in MHB because they move the thermal plume in response to tides, river flow, and winds (Swanson et al., 2006).

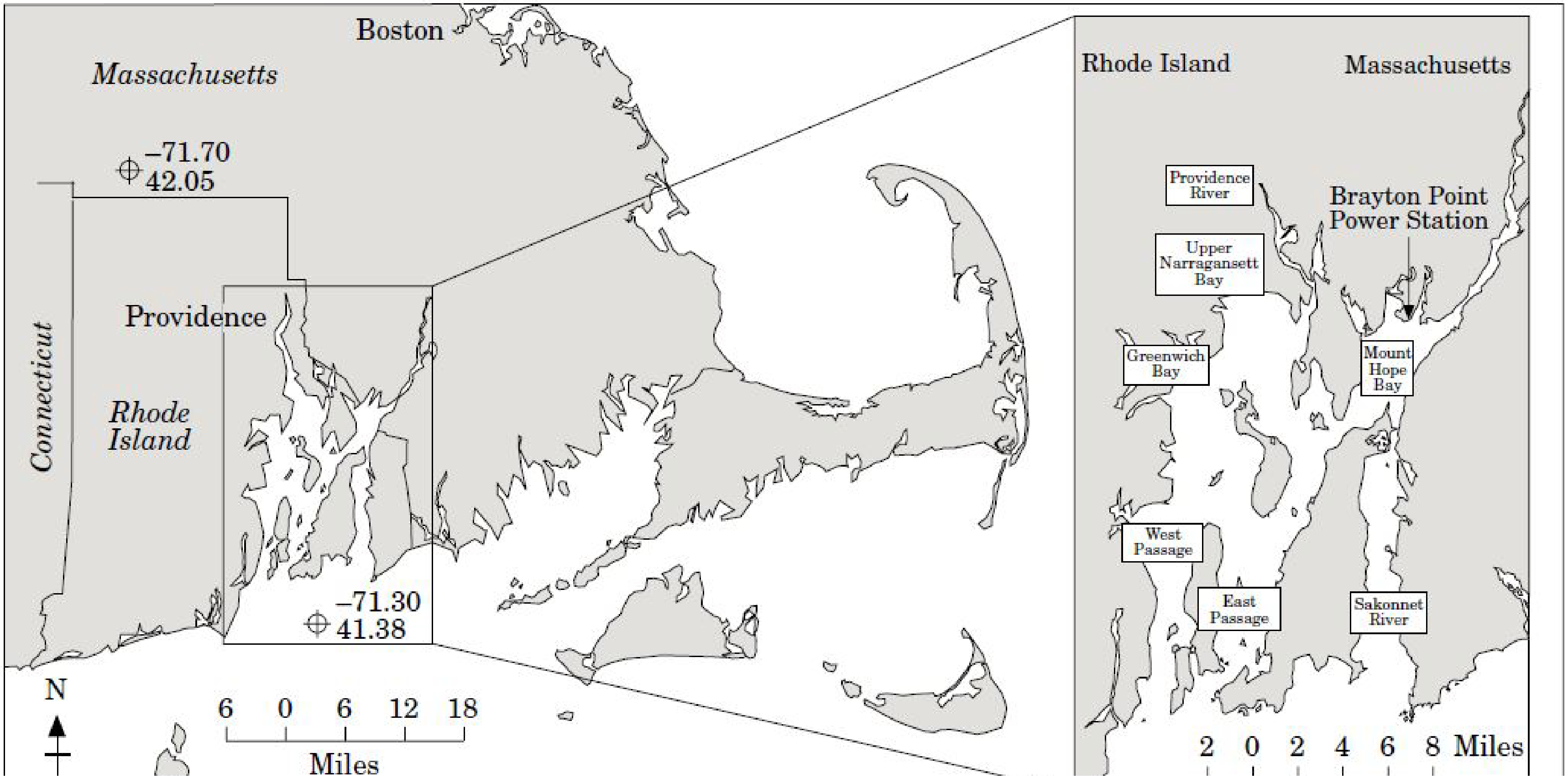

Figure 5-2. Location of BPS in Mt. Hope Bay and Proximity to Narragansett Bay (from Mustard et al., 1999).

RIS

MHB was an important historical spawning and nursery area for a variety of commercially harvested finfish and shellfish and was one of the more productive estuaries in the Northeast (EPA, 2002b). BPS has collected finfish abundance data from six fixed trawl stations in the Bay using consistent methodology since 1972. In addition, biological sampling in MHB has also been regularly conducted by the University of Rhode Island Graduate School of Oceanography (URIGSO) and the Rhode Island Division of Fish and Wildlife (RI DFW). Typical finfish and macroinvertebrate species found in the Bay include: striped bass (*Morone saxatilis*), bluefish (*Pomatomus saltatrix*), winter flounder (*Pseudopleuronectes americanus*) windowpane flounder (*Scophthalmus aquosus*), tautog (*Tautoga onitis*), hogchoker (*Trinectes maculatus*), blue crab (*Callinectes sapidus*), spider crab (*Libinia emarginata*), and horseshoe crab (*Limulus polyphemus*). These species are important members of the BIC found in MHB. Winter flounder, windowpane flounder, hogchoker (a small flatfish), and tautog are resident finfish species of local commercial and recreational importance.

In 1996, RI DFW reviewed the combined data from the three separate sampling programs in MHB (along with appropriate inshore station data from the National Marine Fisheries Service [NMFS]) and evaluated historical trends in fish abundance (Gibson, 1996). At that time, the winter flounder stock in MHB was almost non-existent despite very little fishing activity in the Bay. For 16 of the 21 species examined, the rate of decline in MHB was greater than in neighboring Narragansett Bay. Eliminating other causal factors, RI DFW concluded that the most likely potential source of the ecosystem-wide impact was BPS, due to the large amount of the thermal effluent discharged into the estuary (Gibson, 1996).

In support of this assertion by RI DFW, it was demonstrated that the large increase in the power company's operations in 1984 coincided with a massive decline (87 percent) of MHB’s finfish populations and an accompanying loss in species diversity. Figure 5-3 shows the downward trend in winter flounder following 1984; particularly in the survey data nearest the BPS discharge. Subsequent analysis showed a high negative correlation (R^2>0.85) between thermal effluent totals (in trillions of BTUs) and fish abundance (Gibson, 2002).

Despite this evidence, BPS’s owners initially did not acknowledge that a decline in fish abundance in MHB had occurred and attributed observed changes in fish abundance to sampling gear differences. However, after extensive technical review and evaluation by fishery experts, BPS owners eventually conceded the dramatic decline of fish abundance in MHB starting in 1984 (USGen New England, Inc. (USGenNE), 2001).

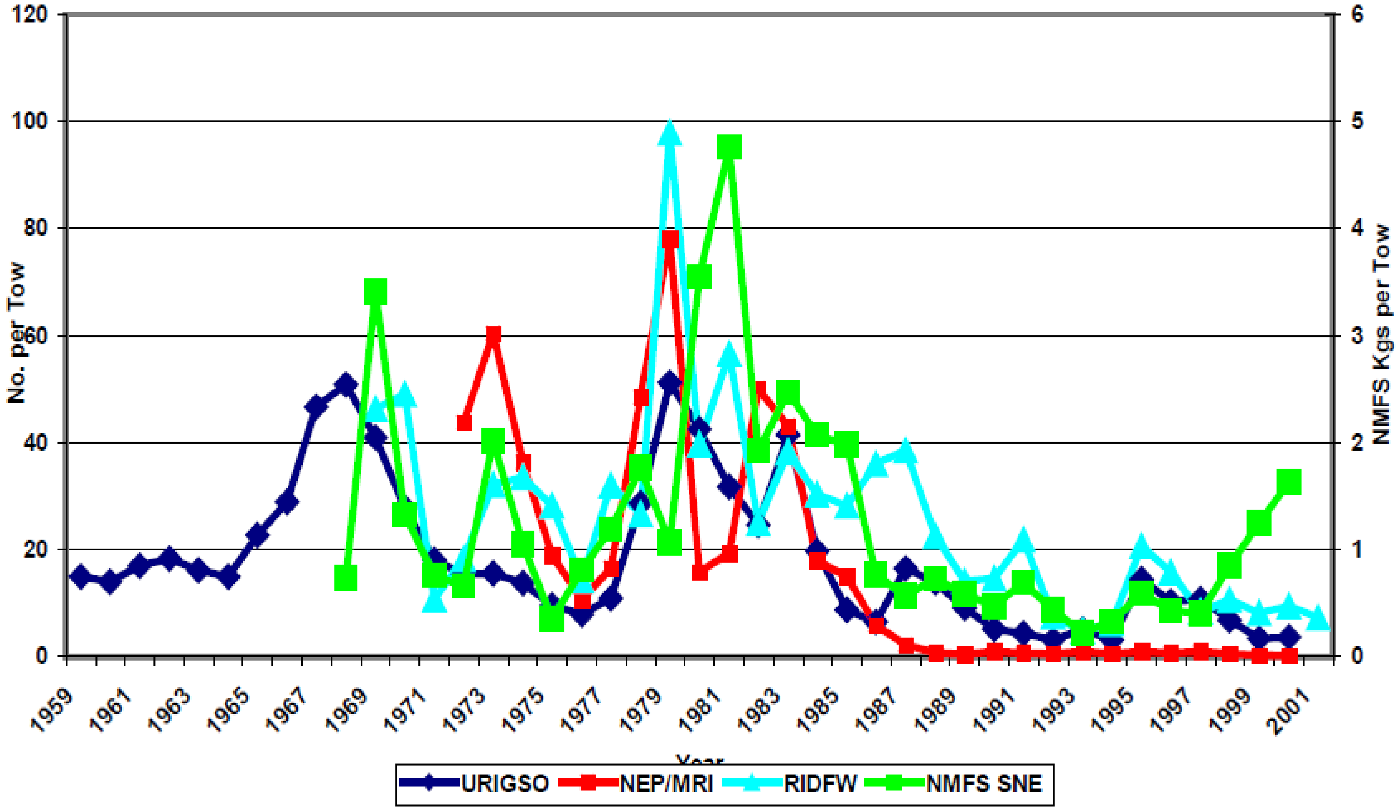

Figure 5-3. Winter Flounder Abundance in Survey Trawls in MHB and Adjacent Waters (1959-2002) From Gibson, 2002; abbreviations in text above).

Section 316(a) Compliance and Thermal Effluent Limitations

Previous compliance with Section 316(a) requirements for the BPS facility thermal effluent limitations and applicable thermal effluent limitations are provided below.

Previous Permits

Construction of BPS Units 1-3 in the 1960s pre-dated enactment of the 1972 CWA and its thermal discharge and cooling water intake structure (CWIS) requirements. The first NPDES permit, issued to BPS in October 1973, restricted thermal discharges to a maximum temperature of 90°F and a change in temperature from intake to discharge (ΔT) of 20°F. Further, due to concerns over potential impacts to the MHB ecosystem, Unit 4, which was then under construction, was required to be operated as a closed-cycle unit. The permit also imposed other general conditions, such as that “the thermal plume shall not block zones of passage ..., interfere with the spawning of fishes . . ., [or] change the BIP of MHB or its tributary waters” (EPA, 2002a).

In the years that followed the issuance of the 1973 NPDES permit, the facility’s operators petitioned for, and were granted, several permit changes that allowed major increases in cooling water withdrawals and thermal discharge (EPA, 2002b). The following changes are among the most significant:

- In 1979, the maximum temperature limit was raised to 95°F and the ΔT limit raised to 22°F;[36]
- In 1982, Unit 4 was allowed to convert to open cycle operations with a new CWIS located on the Lee River; while at the same time, the maximum flow limitation was increased from 915.8 MGD to 1,009 MGD; and
- In 1984, the maximum flow limitation was further increased to 1,452.5 MGD.

As the NPDES permit reached it expiration date in July 1998, BPS had been in operation for nearly 40 years with no significant reductions in thermal discharge over that time, and, in fact, had increased thermal flow into MHB by a substantial amount, through the permit changes listed above.

Thermal Effluent Limitations

BPS discharges thermal effluent into Massachusetts waters but these discharges may also adversely affect Rhode Island waters and biota. As a result, the water quality requirements of both States was considered in the development of the NPDES permit for BPS. The permittee’s re-application for the NDPES permit renewal (USGenNE, 2001) requested extension of the 1993 permit conditions, particularly:

- A maximum temperature limit of 95°F and the ΔT limit of 22°F; and
- A maximum flow limitation of 1,452.5 MGD.

Taken together these requested permit limits would result in an annual mass flux of discharged heat totaling 28 trillion BTUs to MHB (USGenNE, 2001).

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[36] The permitting agencies approved the higher temperature limits under a CWA § 316(a) variance, concluding that the limitations would not interfere with the protection and propagation of a BIC of fish, shellfish and wildlife in and on the receiving water. Fact Sheet, Draft 1993 NPDES Permit No. 0003654, p. 11 (EPA, 2002a).

Thermal Surveys and Modeling

MHB is a good candidate for thermal modeling and biothermal assessment since it is inland and enclosed, has well-defined locations of inflow and outflow, and had a large amount of fish population data and (to a lesser extent) information on physical features and habitats.

The CORMIX model for near-field plume simulation was used for modeling coupled with the proprietary WQMAP,[37] an integrated system for modeling the circulation and water quality of estuarine and coastal waters (Spaulding et al. 1999). The system has a suite of integrated environmental models, including a boundary-conforming grid-generation model, a 3-D hydrodynamic model, and a set of pollutant transport and fate models (single- and multiple-constituent and WASP5 [Water Quality Analysis Simulation Program]). The WQMAP hydrodynamic (or hydrothermal) model can simulate the effects of tide, river flow, air temperature, solar radiation, and wind-induced environmental forcing.

Thermal modeling was supported by an extensive program of hydrographic and thermal mapping observations in MHB undertaken to calibrate and validate the hydrothermal modeling:

- Month-long studies were conducted during the late summer in 1996 and 1997 using several moored instruments, including multi-parameter monitors measuring temperature and salinity, current meters, and a water-level sensor (Swanson et al. 2006). In addition, related data were collected, including light intensity, wind speed and direction, air temperature, river flow, and BPS cooling-water flow and temperature.
- An extensive field program to map the thermal structure in space and time in MHB was conducted. Four major surveys were conducted: May–June 1997, August–September 1997, September 1998, and February–March 1999.
- A series of aircraft overflights using sensors to measure radiance were conducted concurrently with the thermistor in-situ surveys. Seasonal trends of surface temperatures in the Narragansett Bay estuary were derived from a composite of 14 TIR satellite images (Landsat TM 6) with a spatial resolution of 120 m (394 ft).

The August 1997 thermistor monitoring data set was chosen for the calibration set, with input from MHB Technical Advisory Committee (TAC), as it was considered more extensive and complete than the 1996 data set (Swanson et al. 1998). The TAC also advised that the winter 1999 field survey data be used for model verification. The verification process indicated that the hydrothermal model was successful in simulating the 1999 data at multiple time scales (tidal, daily, and weekly).

Several historical and hypothetical scenarios were run to evaluate the effects of reduced discharges of heated effluent incorporating a cooling tower (i.e., enhanced multi-mode operation) as well as the “no discharge” scenario (Swanson et al. 2006). Specifically, the WQMAP hydrothermal model output was processed to generate a series of products needed for the biological assessment:

- Daily averaged total temperatures for water-column volume and bottom area,
- Daily averaged temperature increases over background (no-plant) conditions,

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[37] WQMAP is a proprietary model developed by Applied Science Associates (ASA) Inc. and the University of Rhode Island and is an integrated system for modeling the circulation and water quality of estuarine and coastal waters.

- Distributions of Bay volume and bottom area for a range of total temperatures, and
- Distributions of Bay volume and bottom area for a range of temperature increases over background conditions.

Massachusetts Department of Environmental Protection (MA DEP) assessed the alternative BTU discharge quantities and discharge volumes with respect to the WQMAP model's predictions of the volumetric, cross-sectional and spatial extent of the resulting thermal impacts on MHB and adjoining waters (MA DEP, 2002). The predictions of thermal impacts of each alternative were reviewed to determine whether a potential discharge scenario resulted in a suitable mixing zone that complied with the Massachusetts Surface Water Quality Standard (SWQS) for temperature, including narrative requirements for protection of aquatic life and designated uses of receiving waters.

The model results indicated that the temporal temperature variations occur over tidal to annual time scales. Seasonal variations were most discernible in the shallow upper reaches of the Bay, showing warmer than average temperatures during summer and cooler during winter. In general, MHB modeled temperatures indicated that the BPS thermal discharge exceeded by Massachusetts and Rhode Island SWQS for temperature increase during warm summer conditions throughout more than 70% of the combined Massachusetts and Rhode Island MHB waters (MA DEP, 2002).

Processing of the overflight data indicated that the average temperature difference between MHB and Narragansett Bay during late summer to autumn was 0.8ºC (1.4ºF) and that 35 square kilometers (km^2) (13.5 mi^2) were affected (essentially 100 percent of the Bay) (Mustard et al., 1999).

Section 316(a) Demonstration

The Draft Section 316(a) Technical Guidance Manual recommends that an assessment of thermal impacts be done on a community-by-community (i.e., phytoplankton, zooplankton, habitat formers, finfish) basis (EPA, 1977) and provides decision criteria to judge whether a thermal plume is having a "low potential impact"[38] on the ecological component of interest. EPA Region 1 reviewed the current and historical information on BPS and the BIC in MHB as part of the Section 316(a) community impact analysis (EPA, 2002b) with the following findings.

Phytoplankton Community

EPA could not conclude that BPS was having a low potential impact on phytoplankton in MHB due to the presence of nuisance blue-green algal blooms (*Anacystis auruginosa*) not found in adjacent waters of Narragansett Bay (EPA, 2002a). Due to the proximity of this bloom to the plant discharge and blue-green algae's affinity for higher temperatures, EPA considered it likely that the thermal plume from BPS contributed to this bloom. Both the hydrothermal model and infrared imagery indicated elevation of summer temperature by at least 0.8ºC throughout most of the Bay (Mustard et al., 1999; USGenNE, 2001) and this could lead to changes in phytoplankton population dynamics with possible implications for web dynamics in the Bay. Based on this evidence, EPA could not conclude that BPS was having a low impact to this ecological component (EPA, 2002a).

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[38] Communities showing little or no impact from current operation were deemed by EPA to have low potential impact for thermal effects from future operation assuming other stressors stay constant (EPA, 1977).

Zooplankton Community

EPA assessed possible changes to the zooplankton community which is important in an estuary that serves as a spawning site for numerous fish and invertebrate species. Evidence of changes in the community included the increased presence and earlier seasonal arrival of ctenophore or comb jelly (*Mneimiopsis leidyi*). These ctenophores consume high amounts of zooplankton and pelagic fish eggs and could have indirect effects on finfish abundance (through competition with larval fish over zooplankton). This increased competition for food resources could result in reduced growth rates and survival for larval winter flounder and other species with pelagic larvae. Based on this evidence, EPA could not conclude that BPS was having a low impact to this ecological component (EPA, 2002a).

Habitat Formers

In the past, MHB supported eelgrass beds, an important habitat for spawning and nursery functions for many species. Eelgrass is a cold water plant that ranges from North Carolina to Canada and grows on predominantly soft bottom substrates and MHB should be a good setting for such plants. However, warm water temperatures and low water clarity can reduce existing eelgrass beds and prevent re-establishment (Thayer et al., 1984). EPA considered it possible that the BPS discharge, which elevates the temperature over significant portions of the bay, contributes to the poor success of eelgrass in MHB. Based on this evidence, EPA could not conclude that BPS was having a low impact to this ecological component (EPA, 2002a).

Shellfish and Macroinvertebrates

Shellfish of commercially important species are present in MHB substantial densities. However, EPA did not identify a large quantity of data on shellfish and macroinvertebrate for evaluation. From the existing data, EPA did not find substantial evidence of harm to shellfish and macroinvertebrates from the BPS thermal discharge (EPA, 2002a).

Fish

The bioassessment of fish in MHB relied primarily on two lines of evidence:

- The retrospective examination of the extensive finfish data set documenting the decline and loss of fisheries coincident with higher thermal outputs from BPS starting in 1984; and
- Application of the hydrothermal model results to evaluate potential impacts due to exceedance of specific temperature threshold (both acute and chronic) for individual species, with focus on winter flounder.

As described above, the extensive fishery database allowed analysis of the rapid decline of winter flounder and other species, including assessment of the role of other potential causes (i.e., overfishing, predators (cormorants), and water quality). None of the other causal factors was found to be significant.

Using a series of scenarios with variable plant output and climatic condition, EPA estimated 1) the volume of the Bay that would exceed the critical threshold temperatures for eggs, larval, and sub-adult stages of winter flounder or trigger an avoidance response by striped bass and 2) the duration of the exceedance for various thermal discharge scenarios. The results of the model indicated that significant percentages of the MHB water column or benthic layer would exceed the identified thresholds for extend periods of time (up to the entire year). The findings conclusively supported the negative role of the increased BPS thermal inputs to the Bay. For example, BPS reported that 80 percent of all winter flounder in the trawl surveys were caught at one station, which is one of the deepest points in the Bay and consequently the coolest water temperatures.

Other evidence included the effect of the attraction value of the BPS thermal plume to striped bass and bluefish in the fall and winter, which disrupts their normal migration patterns, and increasing numbers of smallmouth flounder (*Etropus microstomus*), a fish found from Florida to southern New England but whose appearance in increasing in numbers in MHB was attributed to the warmer temperatures.

Based on the weight-of-evidence, EPA could not conclude that BPS was having a low impact to this ecological component (EPA, 2002a).

Vertebrate Wildlife

EPA did not find substantial evidence of harm to vertebrate wildlife from the BPS thermal discharge (EPA, 2002a).

Assessment

The Section 316(a) demonstration for BPS generated considerable controversy and extensive research efforts on the part of both the regulatory agencies and the permittee. It provided a comprehensive examination of potential thermal effects on all components of the BIC as well as examination of other potential causal patterns for the observed data. Ultimately, EPA rejected the Section 316(a) variance-based limits proposed by the permittee because they were not stringent enough for the protection and propagation of the BIC in MHB.

For the 2002 permit, EPA determined that the facility needed to limit its intake of ambient water for cooling to approximately 56 MGD[39] and reduce its heat discharge to MHB from approximately 42 trillion BTUs per year down to 1.7 trillion BTUs per year (EPA, 2002a). These changes required the installation of two 500-ft cooling towers in 2009 (completed in 2013) and discontinuation of BPS authorization to discharge OTCW.

Features/Strengths of the Demonstration

- Used non-proprietary near-field plume model (CORMIX) coupled with a far field model.
- Use of multiple lines-of-evidence to make determination; relying both on hydrothermal model predictions and observed historical trends and current condition.
- Voluminous (>40 years) amount of good quality regional fishery data and integration of data from four sampling programs to document winter flounder (and other species) decline and depleted status.
- Number and depth of secondary supporting technical reports, analyses and expert opinions.
- Comparisons between BIC species status in MHB vs. adjacent Narragansett Bay.
- Detailed, comprehensive analyses of all components of MHB BIC over the entire food web from phytoplankton to vertebrate wildlife.

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[39] The 56 MGD is for make-up water for the two cooling towers (EPA, 2002a).

- Careful evaluation of the potential influence of other causal factors for observed species declines and diversity in MHB.

Weaknesses/Areas for Improvement of the Demonstration

- Scope and level of effort for the 316(a) demonstration resulted in prolonged and costly permitting process.
- Proprietary far-field model (WQMAP).
- Did not explicitly consider impacts of climate change.

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5.3.3 Quad Cities Nuclear Station

The QCNS is a nuclear-powered power plant which draws OTCW from the Mississippi River and discharges heated water back into that waterbody. QCNS completed a Section 316(a) demonstration as part of its request for alternate thermal standards (HDR, 2009).

Facility Characteristics and Environmental Setting

Plant Description

The QCNS (NPDES Permit No. IL0005037) is located on 920 acres in Rock Island County, Illinois on the east bank of the Mississippi River. The Station is located on Pool 14 of the Mississippi River, at river mile 506.5 above the confluence of the Ohio River (Figure 5-4).

QCNS began electrical generation in 1972 and is designed to operate 24 hours a day, seven days a week, with two generating units. Each unit's maximum power level is 2,957 MW, for a combined thermal output of 5,914 MW. Steam, which is produced at high temperature and pressure in the boiler, is exhausted from the turbine of each generating unit and condensed using non-contact cooling water from the Mississippi River. After passing through the condensers, cooling water from Units 1 and 2 mix and then is discharged water through a diffuser pipe system back into the river (HDR, 2009). The diffuser pipe system consists of two 16-ft diameter pipes buried in the riverbed. One pipe extends practically across the river, while the second pipe terminates about 300 ft before the end of the first pipe. Each diffuser pipe is fitted with 20 discharge risers of 36-inch diameter in the deep portion of the river, and 14 discharge risers of 24-inch diameter in the shallow region of the river (Iowa Institute of Hydraulic Research Hydroscience and Engineering (IIHR), 2004).

Environmental Setting

Pool 14 of the Mississippi River is approximately 29 miles in length and encompasses the reach between Lock and Dam 14 at river mile 493.3 and Lock and Dam 13 at river mile 522.[40] Annual river high flows typically occur between April and June and the annual low flows occur between December and February. According to USGS, the mean annual flow at Lock and Dam 14 is 54,114 cfs for the 40-year period (1968-2008) with an estimated 7Q10 (i.e., minimum 7-day flow with a 10-year return period) flow of 13,800 cfs (USGS, 2009).

Mississippi River habitats found near the station include: channel habitat, channel border habitat, side-channel habitat, river, lake, and pond habitat, slough habitat, and island lake habitat (HDR, 2009). These habitats are chiefly classified by location, depth, bottom material, and vegetation. The main channel in the vicinity of the station is characterized by a scoured sand bottom and the highest current velocity. Directly downstream from the station along the Illinois shore are several small islands with adjacent, relatively quiet, shallow water areas. Further downstream, across the main channel, are extensive areas

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[40] The U.S. Army Corps of Engineers maintains the commercial shipping channel and operates the Lock and Dam system on the Upper Mississippi River.

of side channel and slough habitats (HDR, 2009). Major anthropogenic uses of the River at Lock 14 include barge navigation and recreation (boating and fishing).

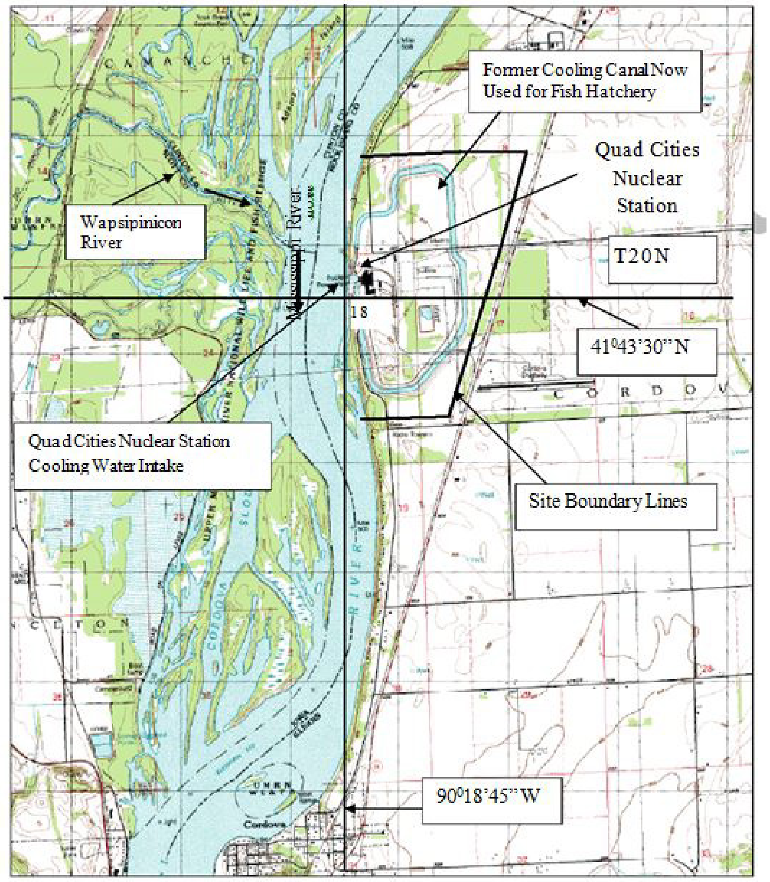

Figure 5-4. Location of Quad Cities Nuclear Station (HDR, 2009)

RIS

Prior biological studies in Pool 14 and adjacent pools in the Mississippi River established the existence of relatively diverse and productive planktonic, periphyton, and benthic communities that support commercial and sport fisheries (HDR, 2009).

Unionid (freshwater mussel) beds are located throughout the study area in a variety of habitats and both upstream and downstream of the QCNS. Thirty-one species of unionid have been collected from Pool 14. The federally endangered Higgins-eye pearly mussel (*Lampsilis higginsii*) was present in seven of the 15 beds sampled (ESI, 2009). Resource agencies in Illinois and Iowa agreed that freshwater unionid mussel communities located throughout the QCNS discharge area warranted a high priority of protection and detailed evaluation under Section 316(a) (HDR, 2009).

Mussel diversity and abundance data were collected in upstream, adjacent and downstream beds. Habitat and water quality information, substrate temperature, and fish communities were sampled at Upstream (UP); Steamboat Slough (SS) (near the QCNS thermal diffuser); and Cordova Beds (CB) areas.

The CB habitat is about one mile downstream from the diffuser and is listed as an Essential Habitat Area for *L. higginsii* by USFWS (USFWS, 2015a).

Mussel density adjacent to the diffuser (SS) was comparable to upstream and downstream beds with similar habitat characteristics. Community characteristics of other unionid beds located further downstream were also very similar to those observed in upstream beds of comparable habitat. Based on these results, HDR (2009) concluded that past QCNS operations have not harmed the unionid community in Pool 14 and that a healthy, balanced community of indigenous species exists. On this basis, no mussel species were explicitly retained as RIS.

A master fish list identified 93 species collected in Pool 14 during the course of 32 years of monitoring studies. Common and numerically-dominant species included: gizzard shad (*Dorosoma cepedianum*), freshwater drum (*Aplodinotus grunniens*), emerald shiner (*Notropis atherinoides*), river shiner (*Notropis blennius*), bullhead minnow (*Pimephales vigilax*), common carp (*Cyprinus carpio*), and bluegill (*Lepomis macrochirus*). Other species regularly collected included: mooneye (*Hiodon tergisus*), river carpsucker (*Carpiodes carpio*), smallmouth buffalo (*Ictiobus bubalus*), shorthead redhorse (*Moxostoma macrolepidotum*), golden redhorse (*Moxostoma erythrurum*), channel catfish (*Ictalurus punctata*), flathead catfish (*Pylodictis olivaris*), white bass (*Morone chrysops*), largemouth bass (*Micropterus salmoides*), black crappie (*Pomoxis nigromaculatus*), sauger (*Sander canadensis*), and walleye (*Sander vitreum*) (HDR, 2009). Pool 14 also provides habitat to paddlefish (*Polyodon spathula*), a proposed species of concern (USFWS, undated), and pallid sturgeon (*Scaphirhynchus albus*), an endangered species (USFWS, 2015b). Field studies of fish communities within the SS Bed indicated little effect of the thermal discharge as comparable communities were found in similar habitats both upstream and downstream of the diffuser.

Screening criteria[41] were developed to identify an appropriate set of RIS including indigenous, riverine fish, including forage fish, threatened or endangered species, recreationally important or commercially valued species. While screening produced a candidate list of 15 species, QCNS ultimately reduced this list to four RIS, citing a lack of good quality thermal tolerance data. The final RIS were channel catfish, largemouth bass, spotfin shiner (*Cyprinella spiloptera*), and walleye.

Section 316(a) Compliance History

Previous compliance with Section 316(a) requirements for the QCNS facility thermal effluent limitations and applicable thermal effluent limitations are provided below.

Previous Studies

ComEd conducted the original Section 316(a) demonstration for QCNS in 1975 with a supplement supplied in 1981 (ComEd, 1975, 1981). The study was jointly approved by the Illinois Environmental Protection Agency (IEPA) and the Iowa Department of Environmental Quality in 1981 (IEPA, 2013).

In addition, a 1-D analytical model was developed and run using data from the summers of 1988 and 1989, a period of unusually low river discharges. Field data from eight surveys during that period were

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[41] Criteria excluded: exotic or hybrid taxa, congeneric (closely related) taxa, taxa not collected within 10 years, captured occasionally, or for which less than 200 specimens had been obtained during monitoring, incidental taxa (e.g., stream fish), and taxa know to have upper avoidance temperature considerably higher than 89°F.

used to evaluate the performance and optimize the existing QCNS diffuser pipe system. The analytical model runs were reported to be in good agreement with the field data (HDR, 2009).

Thermal Effluent Limitations

Thermal discharges from QCNS are regulated by the plant's NPDES permit and the Illinois Pollution Control Board (the "Board") regulations. The existing permit limitations stipulate that discharge of wastewater from the QCNS must not alone, or in combination with other sources, cause the receiving stream (Mississippi River) to violate the following thermal limitations at the edge of the mixing zone:

- Maximum temperature rise above natural (ambient) temperature must not exceed 5°F;
- Water temperature at representative locations in the main river[42] shall not exceed the maximum limits as identified[43] during more than one (1) percent of the hours in the 12-month period ending with any month. Moreover, at no time shall the water temperature at such locations exceed the maximum limits by more than 3°F; and
- The area of diffusion of an effluent in the receiving water is a mixing zone,[44] and that mixing zone shall not extend over more than 25 percent of the cross-sectional area or volume of flow in the Mississippi River or more than 26 acres of the Mississippi River.

Thermal Surveys and Modeling

In September of 2003, a thermal-assessment field study was conducted, measuring surface and vertical-profile temperature downstream in both the Illinois-side navigation channel and the Iowa-side (SS area). These field measurements were complemented by an aerial infrared survey which provided a qualitative view of fate and transport of heat in these reaches (IIHR, 2004). This combined information was used to validate the thermal plume model.

IIHR simulated the Station's thermal plume using a proprietary 3-D CFD code; also known as U^2RANS (Lai et al., 2000). Initial estimates of water-surface elevation were obtained from an earlier proprietary CS2 1-D model covering all of Pool 14 (i.e., from Lock and Dam 14 upstream to Lock and Dam 13).[45] U^2RANS was applied to model the hydrodynamic and thermal characteristics of a Mississippi River reach in the vicinity of QCNS. The results of the simulation provided a detailed 3-D depiction of water temperature and velocities and a single 3-D mesh was developed for simulation of multiple river and diffuser flow conditions. For each of the nine temperature-prediction runs, the temperatures from the computational grid were projected onto verticals beneath each of the surface computational grid points (approximately 95,500 points) for comparison to measured temperatures (IIHR, 2004).

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[42] Main river temperatures are temperatures of those portions of the river essentially similar to and following the same thermal regime as the temperatures of the main flow of the river.

[43] The permit provides an exhibit that lists the maximum thermal limits on a monthly basis.

[44] The mixing zone for QCNS was defined to be a straight line across the Mississippi River 500 feet downstream of the diffuser pipes.

[45] The 1-D model was taken as a subset of a more general one that serves as the basis for the CS2 real-time thermo-hydrodynamic modeling system developed previously for Exelon Generation. This model, based on the CHARIMA computational engine, extended from Lock and Dam 14 all the way upstream to Lock and Dam 11 at Dubuque (IIHR, 2004).

The IIHR modeling effort featured the following major components:

- Inclusion of relevant river-training structures, namely wing dams and the cross-channel closure dam in the nearby SS, within the model bathymetry to better reflect real-world conditions.
- Simulation of conditions corresponding to the HDR September 2003 thermal field survey, to validate the model's ability to predict the observed thermal conditions (Figure 5-5).
- Simulation of QCNS's operations at maximum power over a set of low Mississippi River flows.
- Provision of temperature, depth, and velocity results from the multiple simulations to HDR to serve as input for the biothermal model.
- Supplemental thermal analyses were conducted to correlate with measured sediment temperatures.

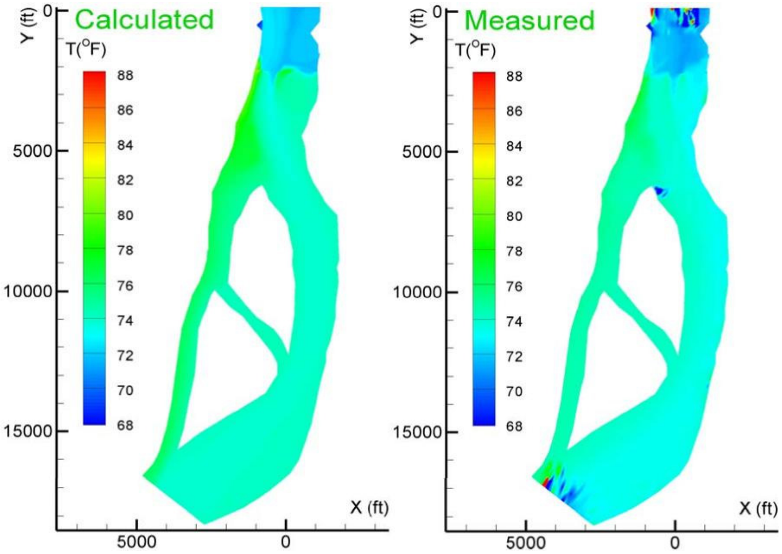

Figure 5-5. Validation Run for QCNS Thermal Plume Study: Comparison between Calculated and Measured Surface Water Temperatures (IIJR, 2004).

The U^2RANS model reproduced temperatures from the September 16-17, 2003 field data campaign without any adjustment of non-physical parameters. The validation effort revealed the importance of including river-training structures such as wing dams and chute closure dams in the model, as they have an important influence on the thermal flow patterns in the vicinity of the QCNS and nearby islands. IEPA, in cooperation with the IDNR, reviewed these results and the model results were considered acceptable (IEPA, 2015).

Section 316(a) Demonstration

The Section 316(a) demonstration analyzed potential adverse effects of the QCNS thermal discharge on the BICs in the vicinity of the facility. This evaluation of potential effects to RIS included three biological parameters: growth,[46] avoidance,[47] and chronic thermal mortality.[48] Potential effects were evaluated for nine scenarios involving assumed (or simulated) river flow rates between 13,800 and 30,000 cfs or actual daily river flow rates (HDR, 2009). For each scenario, the number of excursion hours (i.e., period of exceedance of thermal effluent limitations) that would be experienced during high ambient temperature months (i.e., June through September) was calculated. The biothermal modeling program following the following procedure:

- Obtain spatial and temporal characterization of the QCNS thermal plume through the 3-D CFD model for several river flow conditions;
- Determine acclimation temperatures in each "results grid" cell;[49]
- Determine horizontal and vertical habitats[50] for the RIS in Pool 14;
- Determine the period(s) of the year when the life stages of the RIS inhabit Pool 14 based on biological monitoring programs;
- Determine the growth, avoidance, and chronic mortality temperature tolerances for the four RIS evaluated using temperature tolerance polygons;[51] and
- Apply the preceding inputs to predict the plume's effects on the RIS' biological functions with regard to growth patterns, thermal avoidance, loss of habitat, acute and chronic mortality, etc.

The 316(a) demonstration study postulated that the proposed adjusted standard would not cause any appreciable harm to the RIS evaluated (HDR, 2009). The permittee's assertion that the proposed alternate thermal standard would be adequately protective of the local fish and benthic communities was supported by the low level of impacts predicted in this assessment. IEPA reviewed the model results and bioassessment and renewed approve the permit renewal with the requested thermal variance (IEPA, 2015).

Assessment

The regulatory standard used in a Section 316(a) demonstration is whether a BIC of shellfish, fish, and wildlife has been and will be maintained in or on the receiving waterbody despite the thermal discharge. The IEPA agreed that the standard had been met by the applicant.

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[46] A thermal discharge could shift water temperature into or out of the range conducive to growth in fish.

[47] A thermal avoidance response occurs when fish evade high temperatures because they find them stressful.

[48] Fish that cannot avoid elevated temperatures could potentially succumb to elevated temperatures during a prolonged exposure.

[49] The CFS model grid contained nearly 2 million points. This model output was then distilled into a 50ft by 50ft "results grid" using the Surfer gridding program.

[50] For benthic species, the acclimation and exposure temperatures were determined using the predicted bottom layer temperatures. For pelagic species, the study used average of the full water column.

[51] The temperature tolerance polygon is a diagrammatic presentation of data which demonstrates how temperature tolerances change in response to changing combinations of acclimation and exposure temperatures. The use of temperature tolerance polygons in the river-wide assessment of the plume's biothermal effects accommodates a stochastic analysis that shows the continuous change in predicted biothermal effect over a range of temperatures.

Features/Strengths of the Demonstration

- Model incorporated large number of grid points with special detail regarding local bathymetry and shoreline irregularities (i.e., training structures).
- Model tested a large suite of facility power output and flow scenarios.
- Model validation included both field (boat) surveys and infrared aerial imagery.
- Detailed field studies supporting comparison of unionid habitats and communities upstream, near and downstream.
- Comprehensive biothermal assessment of RIS including multiple potential thermal endpoints (growth, avoidance, and chronic mortality) and consideration of acclimation effects.

Weaknesses / Areas for Improvement

- Number of RIS was limited to four common, widely-distributed finfish despite the wealth of biological monitoring data because of lacking thermal thresholds.
- Failure to include freshwater mussel species into the RIS even though they had been specifically identified as important habitat formers and include an endangered species.
- Modeling used a proprietary model code (U^2RANS) which include preliminary modeling based on a prior proprietary model (CS2).
- Hydrologic conditions evaluated did not explicitly consider climate change scenarios.

QCNS Case Study References

ComEd. 1975. 316(a) & 316(b) Demonstration: A Demonstration to the EPA. Chicago, IL. 262 pp.

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USFWS. (2015a). Midwest Region. Endangered Species: Higgins Eye Pearlymussel *(Lampsilis higginsii)*. Website located at: (http://www.fws.gov/midwest/endangered/clams/higginseye/higgins_fs.html).

USFWS. (2015b). Midwest Region. Endangered Species: Pallid Sturgeon (*Scaphirhynchus albus*). Website located at: http://www.fws.gov/Midwest/endangered/fishes/PallidSturgeon/index.html.

5.3.4 SJEC

The SJEC is a new combined cycle natural gas turbine power plant located on a 165-acre site in New Carlisle, Indiana (IDEM, 2013). SJEC began commercial operations in 2018 (Indiana Utility Regulatory Commission (IURC), 2016). The first phase of construction at SJEC included two 230-MW gas combustion turbines and one 235-MW steam turbine; a second, nearly identical phase is expected to be constructed at a later date.

Facility Characteristics and Environmental Setting

Plant Description

The SJEC (NPDES Permit No. IN0064122) includes two separate 230 MW power units. As part of electricity generation process, the facility also captures exhaust heat from the gas turbines to produce steam, which drives a 235 MW steam turbine. The heated water is sent to cooling towers before being cycled back through the facility (IDEM, 2013). The SJEC is designed with two mechanical draft, ten-cell wet cooling towers (one tower per steam turbine) to dissipate the excess heat (SJEC, 2013). SJEC based the cooling tower design on ambient conditions representative of the peak summer temperatures, when demand for electricity is typically highest. The source of coolant to be used in the cooling towers is groundwater (i.e., treated well water).

The portion of cooling water that does not evaporate from the towers is considered "blowdown." This blowdown, combined with blowdowns from the Project's water treatment units, is discharged to a small, ephemeral stream. The cooling tower design characteristics yielded a ΔT of approximately 10°F between the local environment (i.e., ambient wet bulb temperature) and the cooling tower blowdown (i.e., discharge) temperature during summer conditions (SJEC, 2013). When both units are operating at full capacity during summer conditions, the power plant (as originally proposed) was expected to discharge a maximum of up to 5.9 MGD to the Niespodziany Ditch.

Environmental Setting

The receiving waters for the heated effluent is the Niespodziany Ditch, a tributary to the Kankakee River. The Niespodziany Ditch's location and straight channel morphology suggests that it was originally excavated to collect and transport agricultural and storm event runoff. Current land use practices in the watershed suggest that Niespodziany Ditch flows typically consist of non-point sources including residential and commercial storm water runoff as well as agricultural drainage (SJEC, 2013).

SJEC determined the current flow characteristics and resulting aquatic community in the Niespodziany Ditch through discussions with local officials with historical knowledge of the Niespodziany Ditch and direct observations. SJEC also completed a formal survey of the Niespodziany Ditch from its northern-most point to Indiana State Road 2, completed 37 elevation cross-sections, and conducted detailed flow modeling utilizing HY-8 and HEC-RAS software (SJEC, 2013).

The estimated 7Q10 low flow value is essentially zero, indicating that the Niespodziany Ditch would have negligible flow during drought conditions (IDEM, 2013). However, when SJEC is operating, the Niespodziany Ditch's hydrologic characteristics change from an ephemeral to a perennial stream. During dry weather, the Niespodziany Ditch is an effluent-dominated stream, given the magnitude of the maximum discharge of 5.9 MGD from SJEC. It is likely that downstream transport and localized redistribution of mobile sediments and detritus will occur until hydrologic stability of the channel morphology is reestablished (SJEC, 2013).

Under Indiana WQS, Niespodziany Ditch is presumed to be capable of supporting a well-balanced warm water aquatic community and allowing full body contact recreation in accordance with 327 IAC 2-1-3. However, Indiana's 2012 303(d) List of Impaired Waters identifies Niespodziany Ditch for impaired biotic community.[52]

RIS

Niesponziany Ditch, at the point of the SJEC discharge outfall, is a small ephemeral stream within a narrow riparian corridor. Because of the low-gradient topography, the Niespodziany Ditch provides mostly pool and shallow run habitat when water is available and isolated pools when it is not.

Despite the limited aquatic life habitat near the discharge location, SJEC adopted a conservative approach for identifying RIS.[53] They assumed many forms of aquatic life would potentially migrate upstream into the Niespodziany Ditch's newly-formed perennial stream habitat. Therefore, SJEC's identification of RIS included fish species found in the downstream Laskowski Ditch, nearby Geyer Ditch (tributary to Kankakee River) and the Kankakee River; waterbodies which currently provide much better quality aquatic habitats than the upper portion of the Niespodziany Ditch (SJEC, 2013).

The nearest tributary is Laskowski Ditch located about 1.2 miles downstream (SJEC 2013). Fish species from Laskowski Ditch include: smallmouth bass (*Micropterus dolomieu*), grass pickerel (*Esox americanus vermiculatus*), white sucker (*Catostomus commersonii*), green sunfish (*Lepomis cyanellus*), longear sunfish (*Lepomis megalotis*), mottled sculpin (*Cottus bairdii*), black bullhead (*Ameiurus melas*), bluegill (*Lepomis macrochirus*), lake chubsucker (*Erimyzon sucetta*), western blacknose dace (*Rhinichthys obtusus*), creek chub (*Semotilus atromaculatus*), golden shiner (*Notemigonus crysoleucas),* and central mudminnow (*Umbra limi*) (IDEM, 2008).

These fish represent a wide range of trophic levels including species of forage fish (minnow and mudminnow family plus immature and young stages of catfish, sucker, and sunfish); grazers/detritivores (sucker family, catfish, sculpin); omnivores (all depending upon life stage); insectivores (primarily creek chub, catfish, sunfish), and predators (primarily grass pickerel, creek chub, white sucker and others depending upon life stage) (SJEC, 2013).

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[52] Niespodziany Ditch was identified as assessment unit INK0124_03 for Impaired Biotic Communities (IN.gov undated_1). A TMDL was developed for *Escherichia coli* for the Assessment Unit INK0124_03 in 12-digit HUC 071200010204 for the Kankakee River as part of the Kankakee River/Iroquois River TMDL Study approved by EPA in 2009 (IN.gov undated_2).

[53] "A representative important species is defined as species which are representative, in terms of their biological needs, of a balanced, indigenous community of shellfish, fish and wildlife in the body of water into which a discharge of heat is made." (327 IAC 5-7-2)

The macroinvertebrate assemblage at Laskowski Ditch is dominated by taxa characteristic of temporary waters and isolated pools: (*Gammarus*, *Hyalella*), snails (*Physella*) and water striders (*Gerris* spp.). Several dipterans (true flies and midges) commonly found in either ponds or flowing waters are also present.

A review of the potential RIS categories considered for the Niespodziany Ditch concluded the following:

- **Commercially or recreationally valuable species**: No commercially or recreationally valuable species were identified for the Niespodziany Ditch, either under current or expected future flow conditions. The present recreational value of the Niespodziany Ditch is very poor, but would slightly increase to provide local recreational opportunities (e.g., pleasure fishing or duck hunting).
- **Threatened or endangered species**: There were no available records or field observations that indicated the Niespodziany Ditch as a critical habitat for threatened, endangered, or rare organisms or identified special habitats or species considered being unique to the Niespodziany Ditch. No threatened or endangered species were identified as RIS for the Niespodziany Ditch (under either current or expected future flow conditions).
- **Species critical to the structure and function of the ecological system**: No habitat formers were considered RIS for the Niespodziany Ditch under either current or expected future flow conditions. However, the altered temperature regime is likely to result in faster growth rates and an extended growing period for in-stream algae, bacteria, and macrophytes near the discharge area and downstream towards Laskowski Ditch.
- **Species potentially capable of becoming localized nuisance species**: No species or RIS were identified as capable of becoming a nuisance species in the immediate SJEC discharge area of the Niespodziany Ditch or reaches downstream.
- **Species necessary in the food chain for the wellbeing of other species**: Benthic macroinvertebrates and local fish species were considered RIS organisms as part of the Niespodziany Ditch food chain. Species that could be important in the Niespodziany Ditch food chain would include a range of benthic macroinvertebrates, immature and small fish such as minnow species, and creek chub that serve as a combined forage, grazer, and predator functional organisms.
- **Species that are representative of the thermal requirements of important species**: The fish community was considered the most thermally sensitive group of organisms likely to migrate, colonize, and persist in the Niespodziany Ditch downstream of the SJEC discharge site. RIS were selected to represent thermally sensitive species likely to migrate and occur in the Niespodziany Ditch during spawning periods. These RIS organisms included the creek chub, white sucker, mottled sculpin, and various sunfish.

Section 316(a) Compliance

Previous studies conducted to demonstrate compliance with Section 316(a) requirements for the facility ATELs and the applicable thermal effluent limitations are provided below.

Previous Studies

This was the first NPDES permit application for the power plant. There are no previous site-specific thermal models or biological surveys to draw upon for this site. However, as noted above, fish surveys have been performed in Laskowski Ditch, Geyer Ditch, and the Kankakee River (IDNR, 2008; IDEM, 2009).

Thermal Effluent Limitations

SJEC confirmed in their NPDES permit application that the chemical quality of the blowdown discharge will meet Indiana WQS. However, compliance with the temperature standards applicable to discharges to warm water systems would not feasible due to the projected ambient conditions at the site and expected cooling tower performance projections (SJEC, 2013).

SJEC took a conservative approach in looking at regional fishery information with the understanding that as the Niespodziany Ditch converts from ephemeral to perennial status it is likely that fish and aquatic life will migrate upstream. Accordingly, SJEC's proposed ATELs (90.1°F acute; 80.6°F chronic) were based on survival of the most temperature-sensitive species of the RIS. Based on this rationale, SJEC proposed the ATELs shown in Table 5-2.

Table 5-2. SJEC Proposed Seasonal ATELs.

Month	Alternative Daily Maximum Temperature Limits* °F	Alternative Weekly Average Temperature Limits °F	Rationale
January-May	90.1	80.6	80.6°F MWAT for 100% survival — creek chub; 90.1°F Upper Incipient Lethal Temperature for 50% survival — creek chub
June-September	NA	NA	No change from current regulatory temperature standard
October-November	90.1	80.6	80.6°F MWAT for 100% survival — creek chub; 90.1°F Upper Incipient Lethal Temperature for 50% survival — creek chub

* = Average of day (24-hr) not to be exceeded.
NA = Not applicable

Thermal Surveys and Modeling

The NPDES application included an assessment of the projected effluent temperatures arising from the SJEC facility discharge to the Niespodziany Ditch (IDEM, 2009). To estimate discharge temperatures, SJEC compiled extensive climatic data to characterize ambient conditions at the site.[54] These data were converted to wet bulb temperature and then used to predict discharge temperatures using an empirical relationship between wet bulb and blowdown temperatures.

Based on the predicted temperatures of the SJEC cooling tower blowdown, the facility discharge temperatures were anticipated to exceed the typical range of ambient conditions during the months of January through May and October through December. Predictions indicated that there would be periods when the discharge would exceed the Indiana temperature standards.

Modeling of the winter performance operations indicates that water temperatures exceeding typical ambient ephemeral runoff would be expected to occur within the immediate area of the discharge site and extend downstream to at least the confluence with Laskowski Ditch or less than 0.5 miles. The

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[54] SJEC complied over 50,000 data points for hourly readings of both dry bulb temperature and relative humidity from IDEM and the National Climatic Data Center from January 2006 through September 2012 (SJEC, 2013).

actual downstream extent of the warming influence of the SJEC discharge on the Niespodziany Ditch will ultimately depend upon the ambient air temperature, amount of riparian shading, and water temperature, as influenced by seasonal conditions and the number and magnitude of storm events and runoff (SJEC, 2013).

Section 316(a) Demonstration

SJEC reviewed the major categories of RIS (defined in EPA, 1977) with the assumption that the Niespodziany Ditch would be converted to a perennial stream. The applicant evaluated the potential impact of the projected SJEC discharge on the various RIS, principally benthic and fish communities.

The thermal threshold for mortality common to most benthic macroinvertebrates (i.e., between 35-40°C [95-104°F]) is well above any predicted temperature for the SJEC discharge. However, the increased temperature could have some indirect effects on the benthic community. The increased water temperatures in the Niespodziany Ditch might alter some benthic invertebrate life cycles, diapause (no growth) periods, and/or the timing of emergence. Over time, a shift in the benthic community structure could occur in the Niespodziany Ditch near the discharge (SJEC, 2013).

A balanced trophic assemblage is important and necessary for the stability and long-term sustainability of the food chain. Fish species are an integral component in local food webs for the well-being and support of other species. Fish species reported from regional streams and ditches that are hydrologically connected to the Niespodziany Ditch include numerous trophic roles including: forage fish, grazer/detritivore, insectivore, and predator (SJEC, 2013).

To evaluate survival of fish in the Niespodziany Ditch, the maximum weekly (7-day) average temperature (MWAT) for 100% survival reported for each fish RIS was compared to the projected daily (24-hr) maximum temperature for the SJEC discharge (SJEC 2013). Thermal preferences and tolerances for fish species were obtained from EPA (1977), Wismer and Christie (1987), and various internet resources.

The lowest fish species MWAT for 100% survival was 80.6°F for the creek chub; which also had an upper incipient lethal temperature threshold for 50% survival of 90.1°F. SJEC proposed that the projected weekly average temperatures for the facility discharge during the months of October through May supported 100% survival of the most thermally sensitive fish species. Avoidance and migration capabilities of fish in the Niespodziany Ditch would further support the survival of resident fish.

Assessment

Overall, SJEC argued that the perennial flow of the SJEC discharge will expand available aquatic habitat and provide more stable hydrologic and thermal patterns in the Niespodziany Ditch. They hypothesized that improved habitat conditions should increase the development, species richness and diversity of the benthic assemblage and fish community. SJEC further asserted that thermal regime produced by the discharge would support a complex algal, macroinvertebrate, and fishery assemblage that could serve as a sustainable food chain in support of other species that have the potential to migrate or occur in the Niespodziany Ditch (i.e., birds, wildlife).

In summary, SJEC concluded that the proposed ATELs in the NPDES application were more stringent than necessary to assure the protection and propagation of a BIC of shellfish, fish, and wildlife within the

Niespodziany Ditch. The IDEM agreed with this position and issued their permit in 2013, allowing construction of the facility.

Features/Strengths of the Demonstration

- Analysis of an unusual discharge setting, i.e., a new discharge to an ephemeral waterbody that converts it into a perennial stream. It provides an example potentially applicable to discharges in arid areas or where the effluent discharge dominates the receiving water flow.
- Assessment of the potential changes in physical structure and aquatic habitat quality following the conversion of the stream to perennial.
- Thorough evaluation of potential impacts to major RIS categories, with particular attention on the benthic assemblage and food web considerations for fish species.

Weaknesses/Areas for improvement

- Used a simple thermal model, based on empirical relationship between ambient temperatures and expected blowdown temperatures, to predict discharge temperatures.
- Did not fully explain how discharge heat was dissipated during passage down the Niespodziany Ditch (presumably, it was a combination of thermal cooling with limited dilution).
- No field monitoring data of flow data are available to verify predictions due to low/no flow characteristics of the Niespodziany Ditch.
- Did not field characterize the habitat quality of the projected discharge area directly.
- Did not explore many scenarios of discharge and flow combination.
- Did not explicitly consider climate change scenarios.

SJEC Case Study References

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5.3.5 Valley Power

Wisconsin Electric Power Company (WEPCO), doing business as WE, owns and operates the VAPP. VAPP is a 280-MW natural gas-fired[55] electric power located near downtown Milwaukee, Wisconsin. In 2012, WE submitted a request for an ATEL for the facility's thermal discharge to the Menomonee River via the South Menomonee Canal (WE, 2012a); this request was approved and is included in their current NPDES permit.

Facility Characteristics and Environmental Setting

Plant Description

VAPP (NPDES Permit No. WI-0000931-4) is located on 22 acres in the highly urbanized Menomonee Valley and adjacent to the Menomonee River. The facility is a co-generation facility built in 1969 that provides both electricity for the market (grid) and steam for a downtown Milwaukee district heating system (approximately 450 customers). The facility consists of two steam electric generating units (Unit 1 and Unit 2), each with two gas-fired boilers and a single turbine generator. Each generation unit has a net capacity of 136 MW (WE, 2023).

VAPP's cooling water system withdraws water from the Menomonee River and discharges the non-contact cooling water to the South Menomonee Canal, which travels a short distance before flowing back into the Menomonee River (Figure 5-6). The maximum thermal input of the facility is approximately 1,450 million BTU/hr when the plant is in full operation (WE, 2023).

Environmental Setting

The receiving water is the greater Milwaukee Estuary, which includes the lower portions of the Menomonee, Milwaukee, and Kinnickinnic Rivers, as well as the Outer Harbor area (Figure 5-6). The Menomonee River is classified by the state of Wisconsin as a warm-small waters river.[56] Warm-small waters are waters with an aquatic life use designation of "warm sport fish community" or "warm water forage fish community" with uni-directional 7Q10 flows less than 200 cfs (129 MGD).

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[55] In April 2013, WE filed applications with the Public Service Commission of Wisconsin for approval to convert the VAPP fuel source from coal to natural gas. The plant switched to natural gas in 2015.

[56] Wis. Admin. Code § NR 102.25(2)

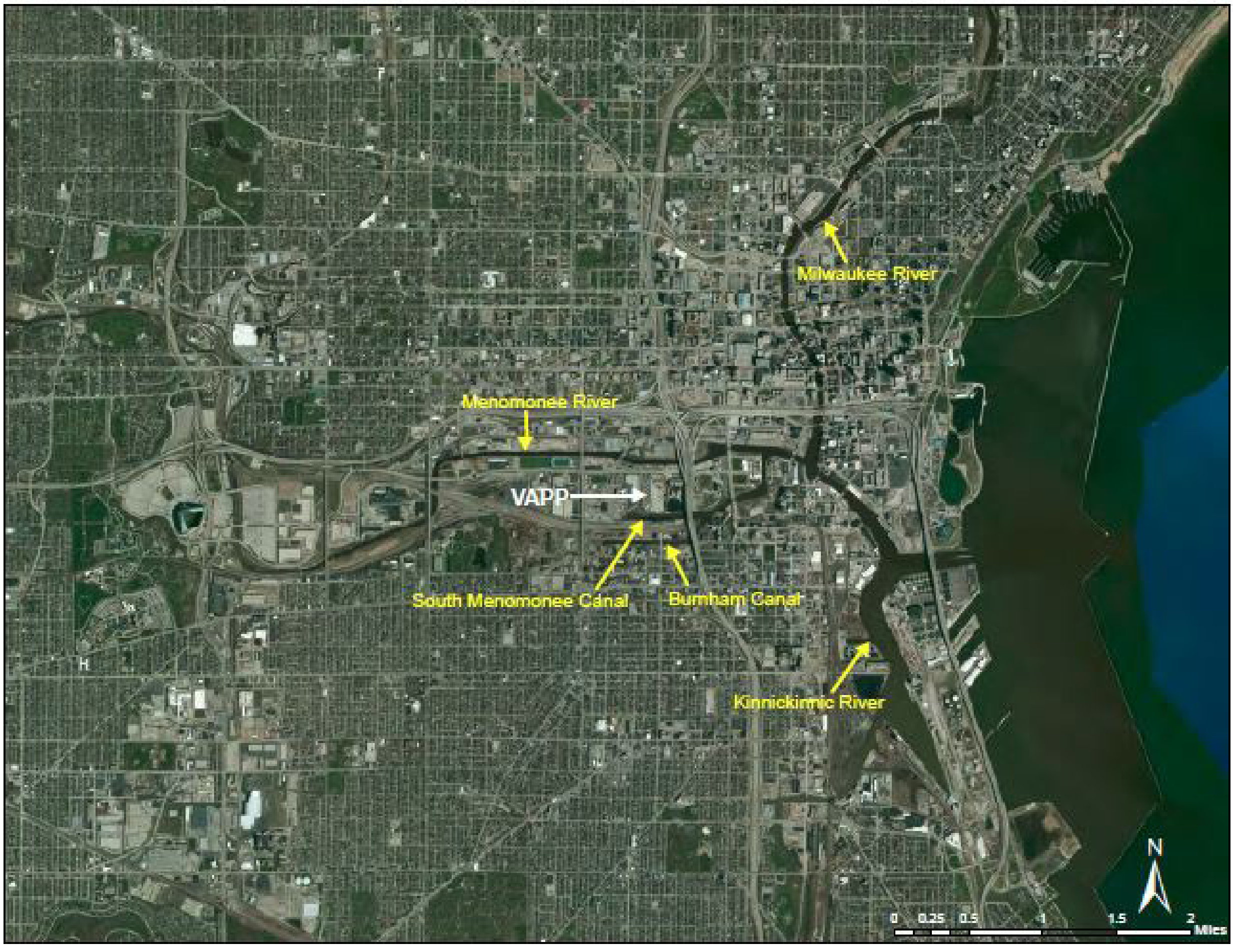

Figure 5-6. Aerial view of VAPP, local receiving waters and Milwaukee Harbor (from WE, 2012a).

The South Menomonee Canal has a variance from meeting the standards for fish and aquatic life and recreational use.[57] It must meet the standards for fish and aquatic life with the following exceptions:

- DO may not fall to less than 2 mg/L at any time,
- The fecal coliform count cannot exceed 1,000 per 100 mL,
- The water temperature cannot exceed 89°F at any time at the edge of the mixing zones.

In the past, water quality in the Milwaukee Harbor was compromised by a number of point sources, including industrial dischargers, sewage treatment plant dischargers, sanitary sewer system flow relief devices, and combined sewer overflows (CSOs) (WE, 2012a). Water quality has greatly improved since the mid-90s due to the installation of the Milwaukee Metropolitan Sewerage District (MMSD) Deep Tunnel[58] system in late 1993. Since the implementation of the Deep Tunnel system, CSO events in the

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[57] Wis. Admin. Code § NR 104.06

[58] The Deep Tunnel system stores combined storm and sewer water until there is sufficient treatment capacity at the wastewater treatment plant.

Milwaukee Harbor have been reduced from over 50 per year to approximately 2 or 3 events per year (MMSD, 2016).

RIS

Inventories of existing habitat in the Milwaukee Harbor Estuary conducted in 1987 identified areas within the Inner Harbor that provided suitable feeding, cover, and spawning habitats for warm water fish, even though habitat conditions were generally poor (WE, 2012a). No new fishery surveys were specifically conducted for this demonstration (AKRF, Inc. 2011). More recent biological monitoring, conducted by the Wisconsin Department of Natural Resources (WDNR) and MMSD over a wider area, were reviewed to identify site-specific RIS.

WDNR *Guidance for Implementation of Wisconsin's Thermal Water Quality Standards* identifies the factors to consider in selecting RIS (WDNR, 2010). These factors include: species with high biomass, species with large numerical abundance, economically important species, thermally sensitive species, or, if present, threatened or endangered species. Additional guidance on RIS selection is available in EPA (1977).

For the VAPP 316(a) demonstration, seven fish species and one invertebrate were approved by WDNR as RIS: northern pike (*Esox lucius*), gizzard shad (*Dorosoma cepedianum*), smallmouth bass (*Micropterus dolomieu*), spottail shiner (*Notropis hudsonius*), walleye (*Sander vitreus*), white sucker (*Catostomus commersonii*), yellow perch (*Perca flavescens*), and side swimmer (*Hyalella azteca*) (WE 2012a). Most of the selected RIS are classified as temperate mesotherms, with ultimate upper incipient lethal temperatures between 82°F and 93°F (WE, 2012a).

Section 316(a) Compliance History

Previous studies conducted to demonstrate compliance with Section 316(a) requirements for the facility ATEL and the applicable thermal effluent limitations are described below.

Previous Studies

A simple thermal model was initially used to predict the expected distribution and pattern of heat dissipation from the facility discharge prior to actual construction (Harleman and Stolzbach 1967). This two-layer stratification model estimated the velocity and temperature distributions under a variety of channel flows to determine whether the planned intake locations could successfully withdraw cooling water from the river year-round.

WEPCO conducted thermal plume surveys in 1975-76 to map the nature and extent of the thermal components of VAPP discharges under varying plant operating conditions, seasons, and river flows. These studies delineated the spatial and temporal limits of Units 1 and 2 plumes under a range of conditions and investigated the plume interaction with the dynamics of the Menomonee River, South Burnham Canal, and South Menomonee Canal (WEPCO, undated).

Additional studies were conducted to characterize the impact of VAPP's thermal discharge on the Menomonee River and its canal system (WEPCO, 1995a, 1995b). One study quantified the warm water distribution within the lower confines of the Menomonee River and canal system during winter (WEPCO 1995a). Another study examined the impact of the VAPP discharge on water circulation and DO levels in the river and canals (WEPCO, 1995b).

Thermal Effluent Limitations

WE requested that the VAPP facility be allowed to operate for 365 days a year with a daily average discharge limitation of 1,450 million BTU/hour. Accordingly, they were required to demonstrate that this output was compliant with the WQS set for the Menomonee River and associated canal system.

Thermal Modeling

WE used an adaptation of ECOMSED, a publicly available coupled hydrothermal and water quality model, to calculate the spatial and temporal distribution of the thermal plume of VAPP's discharge into the Menomonee River and Milwaukee Harbor. ECOMSED was selected because WDNR had previously used the model as part of its Water Quality Initiative,[59] to assess facilities planning and regional water quality in the Milwaukee area with the MMSD.

ECOMSED's hydrodynamic model is a 3-D, time-dependent, circulation model (Blumberg and Mellor, 1985). The model predicts water surface elevation, water velocity in three dimensions, temperature, and water turbulence in response to weather conditions (winds and atmospheric heating and cooling), tributary inflows, and temperature at open boundaries connected to the downstream end of the model domain.

The hydrothermal model was able to simulate the advective and dispersive processes in the Milwaukee Harbor Estuary along the path of the thermal discharge from VAPP. Model calibration used temperature data collected at 25 WDNR water quality stations in the rivers, Outer Harbor, and Lake Michigan during 1995–2002. Water temperature profiles and time-series data were obtained from 25 MMSD sampling stations located in the Milwaukee Harbor Estuary. The model was validated using three longitudinal temperature surveys in the vicinity of VAPP's thermal plume.

The hydrothermal model was run over an 8-year modeling period (i.e., 1995-2002) for two heat load scenarios: "Average Conditions" (1,000 million BTU/hr) and "Upper Bound Conditions" (1,450 million BTU/hr), which represented the median and 95th percentile, respectively, of the average VAPP heat load for 2006-2010. The model calculated water temperatures, both spatially and vertically, within the water column, during all months of the year over the 1995–2002 modeling time period.

The model calculations of water temperature were used to define the extent of elevated temperatures from VAPP's thermal discharge. Outputs from the hydrothermal model were hourly simulations of water temperatures during the modeled time period, which were processed to develop daily-average ambient water temperatures, as well as the departure from ambient temperature (i.e., ΔT) associated with thermal discharge from the VAPP and the corresponding elevated temperatures, calculated as the sum of the ambient temperature and ΔT.

Section 316(a) Demonstration

The Section 316(a) demonstration assessed whether the VAPP thermal discharge assured the protection and propagation of the RIS, and, by extension, maintenance of the BIC of aquatic biota in the Menomonee River and greater Milwaukee Harbor Estuary. A biothermal assessment was conducted

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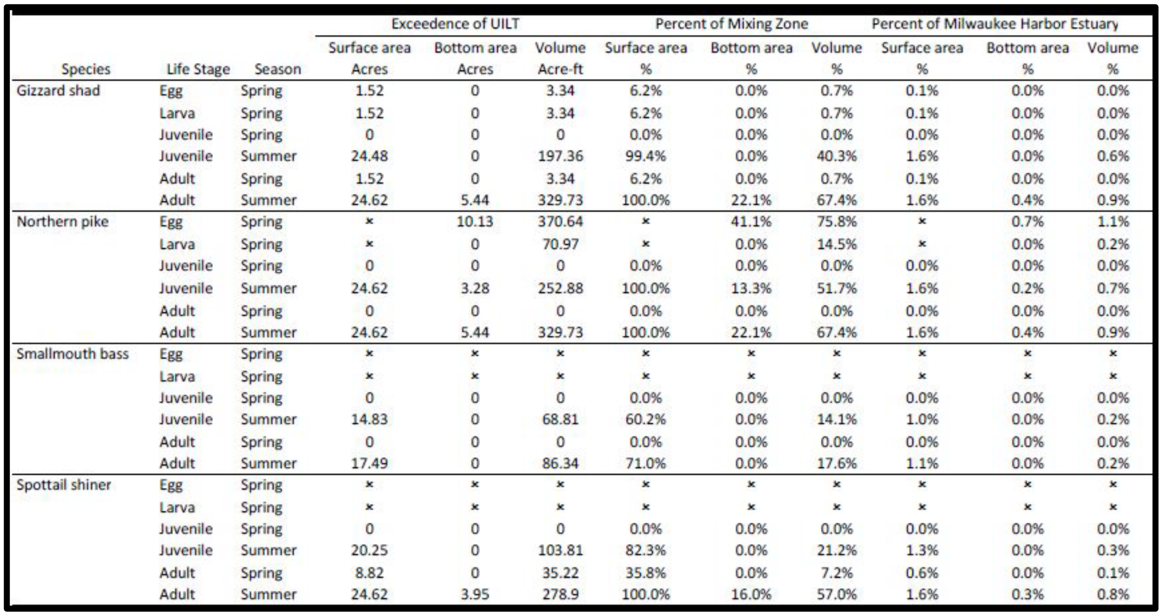
[59] The MMSD, WDNR, and Southeastern Wisconsin Regional Planning Commission formed the Water Quality Initiative. This partnership was the basis for a combined planning effort to assess water resources within the Greater Milwaukee Watersheds.

comparing the predicted water temperature data to RIS-specific temperature thresholds identified for particular life stages (upper avoidance temperatures, upper incipient lethal temperatures, optimal growth temperature, etc.) from the peer-reviewed literature (WE, 2012a).

The potential for adverse temperature-related impact on habitat use, migration, growth, reproduction, and survival was assessed for each RIS. Key biological aspects for maintaining a healthy, stable BIC were considered, including:

- **Habitat exclusion**: This represents the potential for VAPP's thermal discharge to restrict available fish habitat within the Milwaukee Harbor Estuary. The amount of excluded habitat (i.e., area and volume of ΔTs within the thermal plume equal to or greater than the RIS species' temperature thresholds) was calculated as a percentage of the total area of the Milwaukee Harbor Estuary. Examples of this type of calculation and comparison are provided for four RIS in Table 5-3.

Table 5-3. Relative proportions of mixing pone where maximum average temperatures exceed the RIS ULIT under "Upper Bound" Conditions (adapted from WE 2012a).



			Exceedence of UILT			Percent of Mixing Zone			Percent of Milwaukee Harbor Estuary		
			Surface area	Bottom area	Volume	Surface area	Bottom area	Volume	Surface area	Bottom area	Volume
Species	Life Stage	Season	Acres	Acres	Acre-ft	%	%	%	%	%	%
Gizzard shad	Egg	Spring	1.52	0	3.34	6.2%	0.0%	0.7%	0.1%	0.0%	0.0%
	Larva	Spring	1.52	0	3.34	6.2%	0.0%	0.7%	0.1%	0.0%	0.0%
	Juvenile	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Juvenile	Summer	24.48	0	197.36	99.4%	0.0%	40.3%	1.6%	0.0%	0.6%
	Adult	Spring	1.52	0	3.34	6.2%	0.0%	0.7%	0.1%	0.0%	0.0%
	Adult	Summer	24.62	5.44	329.73	100.0%	22.1%	67.4%	1.6%	0.4%	0.9%
Northern pike	Egg	Spring	×	10.13	370.64	×	41.1%	75.8%	×	0.7%	1.1%
	Larva	Spring	×	0	70.97	×	0.0%	14.5%	×	0.0%	0.2%
	Juvenile	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Juvenile	Summer	24.62	3.28	252.88	100.0%	13.3%	51.7%	1.6%	0.2%	0.7%
	Adult	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Adult	Summer	24.62	5.44	329.73	100.0%	22.1%	67.4%	1.6%	0.4%	0.9%
Smallmouth bass	Egg	Spring	×	×	×	×	×	×	×	×	×
	Larva	Spring	×	×	×	×	×	×	×	×	×
	Juvenile	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Juvenile	Summer	14.83	0	68.81	60.2%	0.0%	14.1%	1.0%	0.0%	0.2%
	Adult	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Adult	Summer	17.49	0	86.34	71.0%	0.0%	17.6%	1.1%	0.0%	0.2%
Spottail shiner	Egg	Spring	×	×	×	×	×	×	×	×	×
	Larva	Spring	×	×	×	×	×	×	×	×	×
	Juvenile	Spring	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Juvenile	Summer	20.25	0	103.81	82.3%	0.0%	21.2%	1.3%	0.0%	0.3%
	Adult	Spring	8.82	0	35.22	35.8%	0.0%	7.2%	0.6%	0.0%	0.1%
	Adult	Summer	24.62	3.95	278.9	100.0%	16.0%	57.0%	1.6%	0.3%	0.8%

- **Zone of passage**: The available percentage of the zone of passage was evaluated for each RIS by comparing the upper avoidance temperature to the summer predicted water temperatures found in cross-sectional areas at the confluence of the Menomonee River and the South Menomonee Canal.
- **Reproduction, spawning and growth**: Thermal discharge impacts on reproduction, spawning, and growth of RIS were evaluated by considering species-specific spawning and hatching temperatures, optimal growth temperatures, and no-growth limits in comparison to thermal conditions within VAPP's thermal plume during the spawning season and during peak annual (summer) temperatures.
- **Heat shock**: Potential mortality from exposure to elevated temperatures was assessed. Relevant biological and life history factors were also considered, including spawning season and location, ambient water temperatures, and the ΔT due to VAPP's thermal discharge.

- **Cold shock**: The potential for cold shock was examined by plotting the daily average ambient and elevated water temperatures for the Upper Bound Conditions at the confluence of the Menomonee River and South Menomonee Canal over the course of the winter months. The analysis was performed for three operating scenarios: (1) both VAPP units in operation, (2) one-VAPP unit shuts down, and (3) both VAPP units shut down.

Based on the analyses described above, WE concluded that the proposed ATEL would ensure the protection and propagation of RIS populations and, by extension, the maintenance of the local BIC.

Assessment

The Section 316(a) demonstration concluded that the proposed thermal discharge from VAPP under the requested ATEL would allow the continued protection and propagation of a BIC of shellfish, fish, and wildlife in and on the body of the Menomonee River. This conclusion was based on the evaluation of the spatial and temporal distribution of elevated temperatures in the Milwaukee Harbor Estuary, the potential for acute and sublethal effects on the RIS, and a review of information on the species composition and relative abundance of the fish community in the Milwaukee Harbor Estuary.

WDNR and EPA reviewed the application for the ATEL and incorporated the alternative limits in the current permit.

Features/Strengths of the Demonstration

- Used non-proprietary model (that may no longer be available).
- Model dealt with complex receiving water environment (river, canals, harbor).
- Study included thorough evaluation of direct and indirect thermal impacts (i.e., thermal exclusion; zone of passage; growth, reproduction, and spawning; heat shock; and cold shock) on the RIS.
- Modeling effort used long-term monitoring database for calibration.
- Study also considered the interaction of water temperature and water quality (toxics) on RIS (not discussed in this case study summary).

Weaknesses/Areas for Improvement

- No thermal survey was conducted and thermal modeling relied on old data that may or may not represent current conditions.
- No site-specific ecological surveys were made to identify current BIC and habitat. Instead, used old or regional biological data for RIS selection.
- No plant or habitat formers were included as RIS (this may be partially justified due to poor quality of the benthic habitat).
- Did not explicitly consider climate change scenarios.

Valley Power Case Study References

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5.3.6 Vermont Yankee Nuclear Power Station (VYNPS)

The VYNPS was a nuclear-powered power plant located in Vernon, Vermont. VYNPS drew OTCW from the Connecticut River and discharged heated water back into that waterbody. VYNPS completed a Section 316(a) demonstration as part of its 2004 request for ATELs (Normandeau Associates, Inc (NAI), 2004).

Facility Characteristics and Environmental Setting

Plant Description

The VYNPS (NPDES Permit No. VT0000264) is located on Vernon Pool, an impounded reach of the Connecticut River, located 0.75 miles upstream of Vernon Dam. The station was a 620 MW nuclear reactor. VYNPS began operating in 1972 and was closed in December 2014.

VYNPS could operate under open cycle, closed cycle, or hybrid cycle, resulting in variable discharge temperature and volume. The station drew cooling water from the lowermost reach of Vernon Pool and, depending on the station's operating mode, would return all, a portion, or none of the cooling water to

Vernon Pool as heated effluent. Cooling water returned to the Connecticut River through the discharge structure near the riverbank southeast of VYNPS. The discharge structure was approximately 199 ft long by 108 ft wide by 46 ft deep and consisted of an aerating spillway that provided air entrainment, energy dissipation, and warm water dispersion of the discharged cooling water (USNRC, 2007).

The typical temperature range of the thermal discharge during the warmer summer months was approximately 80 to 90°F, with a maximum of about 100°F. Discharge volume varied between 0 MGD during closed cycle operations to slightly over 430 MGD in the maximum OTCW mode operation (NAI, 2004).

Environmental Setting

The receiving water is Vernon Pool, a 2,481-acre impoundment of the Connecticut River, containing 193.66 million ft^3 at its full-pond elevation (NAI, 2004). The Connecticut River forms the border between Vermont and New Hampshire and Vernon Dam is located 3 miles north of the Massachusetts border (Figure 5-7).

The Connecticut River is the largest river in New England. Its watershed is more than 11,250 mi^2 with the main branch flowing south 416 miles from Canada to its outlet in the Long Island Sound. The average flow in the Connecticut River near VYNPS is 10,652 cfs with a minimum flow of 305 cfs (USGS 2016). Water withdrawals from the tributaries and mainstem are used for irrigation, industrial use, or to support fish hatcheries (Connecticut River Joint Commission, 2008).

Flows in the Connecticut River are highly controlled by hydroelectric generation activities upstream and downstream of VYNPS. There are nine hydroelectric dams and three storage dams on the mainstem Connecticut River upstream of Vernon Dam, and three hydroelectric dams and one pumped-storage facility downstream. The upriver stations and VYNPS were generally operated in unison to maximize power output during times of peak power demand. The amount of heat that can be discharged by VYNPS depended on plant operational mode, the upstream hydroelectric systems, and ambient river temperature (NAI, 2004).

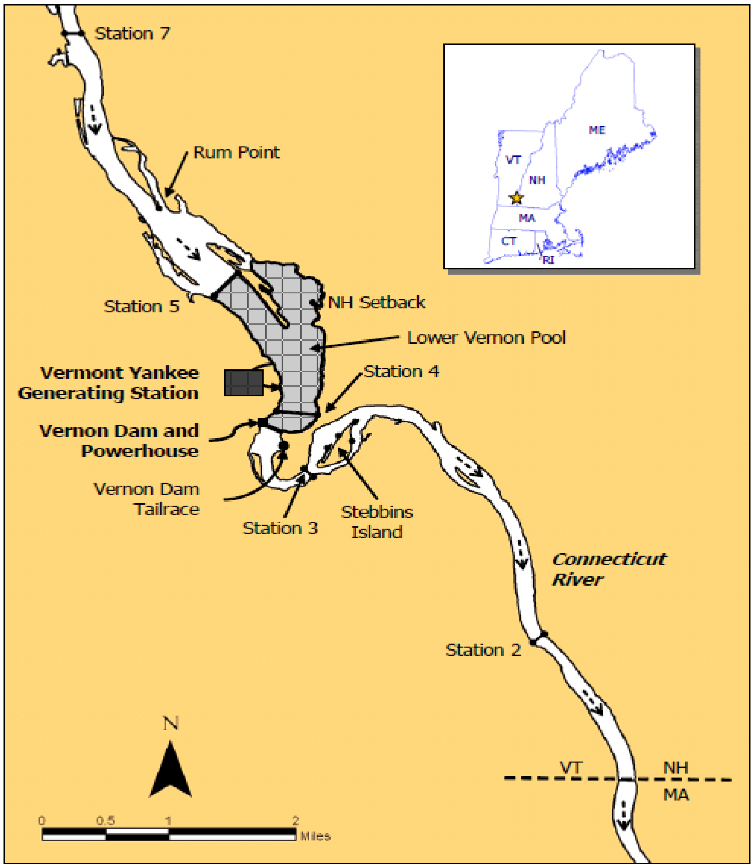

Figure 5-7. Connecticut River near VYPNS showing Vernon Pool and Dam (from NAI, 2004)

RIS

The Connecticut River is the most significant source of aquatic habitat and resources in its watershed and supports cold, cool, and warm-water fisheries with over 142 fish species throughout its length (USFWS, 2015). In the Vernon Pool reach, migratory fish species such as Atlantic salmon, American shad, and river herring are found, as well as resident fish species, an endangered mussel, (dwarf wedgemussel [*Alasmidonta heterodon]*) and endangered plants (Northeastern bulrush [*Scirpus ancistrochaetus]*) (USFWS, 2015, 2016).

Six RIS were selected from previous Section 316 demonstrations, based upon the 30 years of monitoring data (Downey et al. 1990). These species included American shad (*Alosa pseudoharengus*), Atlantic salmon (*Salmo salar*), spottail shiner (*Notropis hudsonius*), smallmouth bass (*Micropterus dolomieu*), yellow perch (*Perca flavescens*), and walleye (*Sander vitreum*). The 2004 demonstration added three additional fish species to the RIS list: largemouth bass (*Micropterus salmoides*), fallfish (*Semotilus corporalis*), and white sucker (*Catostomus commersonii*) (NAI, 2004).

The nine RIS considered in the 2004 demonstration are important members of the BIC found in the Vernon Pool reach (NAI, 2004). At the time of the 2004 demonstration, restoration programs for both

American shad and Atlantic salmon were active.[60] These programs were attempting to increase numbers of these anadromous species to the river through fish passage improvements and trap and transport programs in order to make the populations more self-sustainable for sport fisheries. The spottail shiner, smallmouth bass, and largemouth bass are numerically important members of the BIC. The spottail shiner is a significant prey item, whereas the smallmouth and largemouth bass are piscivorous predators. Fallfish was selected because it is considered intermediate in its pollution tolerance, whereas white sucker is considered an omnivore that is tolerant of pollution. Yellow perch is a recreationally important panfish, as well as a non-migratory species that is reported to be intermediate in its pollution tolerance. Walleye is not an abundant species in the vicinity of VYNPS, but it is a species valued by anglers and found in both lentic and lotic habitats.

The selected RIS include both lentic and lotic habitat guilds of fish species representing the fish communities in slow-flowing, ponded areas such as lower Vernon Pool as well as those which inhabit the turbulent Vernon Dam tailrace. The nine species include different trophic and tolerance guilds based on their feeding habits and tolerance to non-specific environmental stressors.

A prior demonstration (1990) classified the phytoplankton, zooplankton, and benthic macroinvertebrate communities as "low potential impact" biotic categories of little use as RIS. However, benthic macroinvertebrates were still monitored from 1991-2002. None of these ecological communities were selected as RIS in the 2004 demonstration (NAI, 2004).

Section 316(a) Compliance History

Previous studies conducted to demonstrate compliance with Section 316(a) requirements for the facility ATELs and the applicable thermal effluent limitations are provided below.

Previous Studies

Environmental monitoring was performed in the Connecticut River in the vicinity of VYNPS for decades. These monitoring studies provided information for a wide range of thermal discharge conditions including the pre-operation period as well as under the station's three operating cycles. VYNPS was first permitted (in 1973) to discharge as a closed-cycle cooling operation. The station operated in this capacity until 1974 when testing of open-cycle cooling operations began.

Two Section 316(a) demonstrations were conducted following the shift in cooling methods and supported successful requests for ATELs (Binkerd et al., 1978; Downey et al., 1990). Binkerd et al. (1978) presented data from pre-operational field studies and hydrological and biological studies performed during selected periods of open-cycle operations between 1974 and 1977. Based on this demonstration, VYNPS was permitted to operate in open-cycle mode during the winter period (i.e., November 15–May 15). These thermal discharge effluent limits were in place from 1974 to 1990.

In 1990, a Section 316(a) demonstration reviewed the field monitoring period from 1981 through 1989 as part of Project SAVE (Save Available Vermont Energy), a 10-year effort to maximize the plant's energy production without increasing environmental impact (Downey et al., 1990). The demonstration used biological data and results from 20 years of monitoring and studies as the basis for a bioassessment of

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[60] As of 2012, USFWS stopped culturing of Atlantic salmon for restoration but restoration of shad populations is still ongoing (USFWS, 2016).

the aquatic community. The studies indicated that a 1°F to 5°F increase in mixed river temperature (depending on upriver ambient water temperature) during open or hybrid cycle operation would be protective of the warm water fish community. The proposed ATELs were accepted and incorporated into the VYNPS's NPDES Permit as summer limits (NAI, 2004).

Thermal Effluent Limitations

Thermal discharges from VYNPS were regulated by the plant's NPDES Permit and the Vermont WQS. Permit limitations stipulated that discharge flows from the VYNPS could not exceed 543 MGD when operating open- or hybrid-cycle and 12.1 MGD when operating closed-cycle.

Seasonal limits were set for four periods: winter period (October 16–March 31); spring period (April 1–June 30); summer period (July 1–September 15); and fall period (September 16–October 15). For each of these periods, a not-to-exceed absolute temperature limit for the downstream monitoring station, Station 3 (see Figure 5-7) was established: winter (65°F), spring (71°F), summer (85°F), and fall (69°F). In cases of exceedance, VYNPS was required to reduce the thermal output of the discharge to reduce the average hourly temperature at Station 3 below these thresholds (EPA 2014). In addition, the relative increase in temperature above ambient[61] or ΔT (as measured at upstream monitoring station, Station 7 [Figure 5-7]) was limited to between 2°F and 5°F, depending on the season and the ambient water temperature, with greater increases associated with colder ambient water temperatures.

Thermal Surveys and Modeling

The 2004 demonstration built on thermal studies conducted for VYNPS in support of previous Section 316 demonstrations (Binkerd et al., 1978; Johnston, 1984; and Luxemberg, 1990a, 1990b). Specifically, hydrological and thermal monitoring performed during the summer periods of 1998–2002 was used in the 2004 demonstration. Additional monitoring was conducted to establish recent flow conditions and to confirm that these flows were similar to historical data to ensure that the data provided a strong basis for predicting thermal conditions changes under the proposed ATEL request. NAI (2004) used flow duration curves for hourly, daily, monthly, and seasonal flows to confirm that the conditions in the period 1998–2002 were similar to conditions in the last 30 years.

Similar analyses were performed with the temperature data to ensure that recent temperature conditions matched historical conditions. Water temperature data were not readily available so air temperature records were used to compare the recent and historical temperature conditions. NAI (2004) concluded that monthly temperatures experienced from 1998–2002 were representative of the historical record.

VYNPS NPDES thermal limits were determined by calculating the temperature rise that would result after complete mixing of the discharge with the river, using the ΔT equation initially proposed in the 1978 Section 316 demonstration (Binkerd et al., 1978). The 2004 demonstrations showed that the existing ΔT was almost always less than the 2°F limit. This demonstration also calculated the magnitude of temperature exceedance at the downstream station (Station 3) during the summer season. The ATEL request would increase the temperature in the river by 1°F or less in the summer months (NAI, 2004).

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[61] The increase in temperature above ambient conditions (ΔT) was interpreted to represent the plant induced temperature increase as calculated by an empirical equation (defined in Binkerd et al., 1978).

A proprietary 3-D time-varying hydrothermal model, BFHYDRO[62] (ASA, 1996), was developed, calibrated, and used to predict the extent of the station's thermal plume under existing conditions and proposed new summer thermal discharge limits. The objectives of hydrothermal modeling were to: 1) forecast changes in the River thermal regime of the lower Vernon Pool under existing and proposed new summer thermal discharge limits, 2) quantify the gain or loss of fish habitat with respect to the forecasted thermal regime changes, and 3) predict the effects, if any, of the proposed new thermal discharge limits on water temperatures in the Vernon Dam fishway (NAI, 2004).

The model was calibrated with hourly flows and temperatures from five summer periods (July-August) from 1998–2002. The applicant modeled the warmest months, July and August, rather than the entire summer period, to provide a conservative estimate of potential effects. The model analyzed the predicted thermal plume volume in lower Vernon Pool under the proposed and existing conditions and used the results to demonstrate that the BIC of aquatic biota had been and would be maintained under the proposed limits (NAI, 2004).

Section 316(a) Demonstration

The Section 316(a) demonstration combined the results of thermal modeling with a biothermal assessment to analyze potential adverse effects of the VYNPS' current and proposed thermal discharge on the BIC. This demonstration also considered the effects on the benthic macroinvertebrate populations, adult and larval fish populations, and fish passage at Vernon Dam.

Annual time series of each major grouping of macroinvertebrate catch per unit effort were analyzed using the non-parametric Mann-Kendall test to evaluate trends in macroinvertebrate populations during the period 1996-2002. This analysis found that macroinvertebrate relative species abundance and catch effort have remained nearly constant during the annual 1991 to 2002 monitoring programs. The study concluded that the macroinvertebrate community in the vicinity of VYNPS had maintained a stable community composition from 1991 to 2002.

Trends in the fish community in the vicinity of VYNPS were analyzed using 1991-2002 data from routine sampling, as well as the larger data set which covered over 30 years (Downey et al., 1990). The data confirmed a general similarity in community composition over the three review periods: 1968–1980, 1981–1989, and 1991–2002. The study concluded that none of the observed changes in fish community composition or distribution over the 33-year study period could reasonably be attributed to the operation of VYNPS.

The Section 316(a) demonstration study concluded that the proposed increase in thermal discharge would not impact successful completion of life cycles of the indigenous species or the passage and spawning of the re-introduced migratory species (i.e., shad and salmon), and assured the protection and propagation of the local BIC (NAI, 2004).

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[62] BFHYDRO is the hydrodynamic model component of the proprietary WQMAP model package (ASA, 2001). BFHYDRO solves the 3-D conservation of water mass, momentum, salt and energy equations on a spherical, non-orthogonal boundary conforming grid system and is applicable for estuarine and coastal areas (e.g., BPS and Mt. Hope Bay – see Section 5.3.2).

Assessment

Based on the review of the long-term monitoring database of the abundance and composition of fish and other aquatic communities, and their successful persistence over the period when the alternative thermal standards were in place, the permit applicants were successful in retaining these alternative standards in the reissued permit.

Features/Strengths of the Demonstration

- An extensive monitoring database of fishery surveys and benthic investigations to validate selection of RIS.
- Use of large ecological database to run scientifically-conclusive statistical tests to detect potential trends (or lack thereof) over many years of plant operation.
- Consideration of aquatic communities both within the Vernon Pool (lentic habitat) and in the downstream tail race area (lotic habitat).
- Use of three previous Section 316(a) demonstrations (e.g., 1978, 1986, and 1990), which provided confidence in adjusting seasonal alternative thermal limits.
- Use of a transparent method of determining compliance through measurement and comparison at two (upstream and downstream) monitoring stations.

Weaknesses/Areas for Improvement

- No discussion of how optimization of cooling operations (i.e., open cycle, closed cycle, or hybrid cycle) may minimize thermal effects.
- Proprietary model was used.
- Conditions evaluated did not explicitly consider climate change scenarios.

VYNPS Case Study References

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5.4 Review of Thermal Study Key Design Elements

The case studies described above provide examples of Section 316(a) demonstrations that successfully assessed the facility's potential thermal impacts and provided a scientifically-defensible rationale for supporting or adjusting existing NPDES permit effluent limitations. These studies are uniquely tailored to their location and environmental settings, subject to the practical limitations of available historical data, and influenced by previous permitting activities.

Many of these case studies present detailed approaches to certain technical areas or scenarios while other elements are less-well developed or, in some cases, lacking. None of the individual case studies provide an ideal approach to use for all Section 316(a) or thermal mixing zone studies. However, comparison of these studies did identify some useful study design elements that may be important to consider for both permit applicants or and regulatory reviewers when developing or reviewing a workplan for a Section 316(a) demonstration or related thermal mixing study. These useful study design elements are summarized below as Recommended Best Practices for each of the thermal study key design elements: current environmental characterization; overlapping regulatory zones and ecological habitats; long-term monitoring data; RIS selection; thermal monitoring; selection of thermal mixing models; thermal modeling scenarios; and bioassessments.

5.4.1 Current Environmental Characterization

The study design workplan elements should include characterization of the current status of the receiving waters and physical environment subject to the thermal discharge and plume, in both the immediate (near-field) and downstream or regional areas (far-field). A current or updated characterization is recommended because data drawn from older Section 316(a) demonstrations or thermal studies may not be representative of the current physical structure (bathymetry, substrate), water quality, or habitat quality of the receiving water. In addition, the study should also clearly describe the outfall location, diffuser design, discharge depth, and water depth at the discharge point, since all of these factors affect the near-field thermal plume mixing and transport.

Physical Environment Characterization

Many primary 316(a) studies done in the 1970s and 1980s employed a relatively simple model of the receiving waters; often requiring little information regarding bottom structure, bathymetry, or shoreline structures complexity. Physical attributes can be altered over time due to anthropogenic (e.g., dredging, deposition, shoreline development), natural means (i.e., changes in water elevation, shifting river currents, storm events), or other causes.

Several case studies updated this basic information through field reconnaissance survey. QCNS identified and mapped shoreline wing walls and sub-surface structure built to direct ("train') river flow (HDR, 2009). BP collected data on physical macrohabitat attributes including substrate, cover type, shoreline morphology, and riparian zone and band erosion (EA 2002). VAPP performed several ancillary studies to better characterize flow and depths during various seasons within the relatively complex Menomonee River canal system (WE, 2012).

Recommended Best Practices: A study plan should include field reconnaissance to confirm or map waterbody bathymetry, identify substrate composition, and note new shoreline alterations. This information should be transferred to a digital (GIS) base map for use in planning thermal and/or biological surveys. The exact scope of the reconnaissance survey can be adjusted according to the availability of recent, good quality information.

Water and Sediment Quality Characterization

Water quality and sediment quality in some receiving waters has improved over the last 25 years, due to many reasons, including: CWA and Clean Air Act permitting requirements, improved wastewater technology, reduced organic loading, toxic reduction programs, more stringent discharge effluent limitations, dam removal, elimination of urban CSOs, and better stormwater management and control (e.g., municipal separate storm sewer system (MS4) permitting). Improved water and sediment quality can increase the numbers and diversity of local fish and benthic communities. This knowledge should improve the representativeness of RIS selection and aid in the design of biological surveys. Improvements may be more noticeable in developed harbor areas historically subject to water and sediment pollution. Facilities discharging to a marine environment or major river may be able to use water quality or sediment data available from existing sources (e.g., NOAA, USGS National Water Quality Assessment, state resource agencies, or local academic institutions).

For example, VAPP collected water and sediment quality data from local receiving waters to evaluate the effects of the implementation of the “Deep Tunnel” CSO abatement structure and determine the potential influence of two local Superfund sites (WE, 2012). This allowed VAPP to examine potential impacts to RIS due to non-thermal physiochemical factors: low DO, residual chlorine, heavy metals (copper, nickel and selenium) and organic compounds such as polychlorinated biphenyls (PCBs).

In environments known to be heavily polluted, it may be necessary to review the ambient levels and toxicity of such contaminants or evaluate potential temperature-chemical interactions (e.g., DO, ammonia) to be able to isolate the true role of temperature in shaping the local biotic community. Being able to evaluate and eliminate other causal factors for observed fishery trends was particularly important for the BPS demonstration (EPA, 2002).

Recommended Best Practices: Local water quality and sediment quality should be characterized, particularly in areas subject to historical discharge of toxics, nutrients, or with impaired water uses (e.g., Section 303(d) listed waters). This ancillary information should be useful in refining RIS lists and interpreting patterns of presence, abundance, or diversity of species with regard to the role of non-thermal causal factors.

5.4.2 Overlapping Regulatory Zones and Ecological Habitats

Thermal discharges typically contain overlapping zones of regulatory and ecological interest. The size, volume, shape, and seasonal limits of a thermal mixing zone will be delineated through thermal monitoring and modeling (see below). Within these limits, it is important to identify site-specific, critical ecological sub-habitats including: zones of passage for transient fish, spawning areas and nursery areas for resident fish, and/or location of habitat formers (e.g., freshwater mussels, eelgrass).

Various life stages (eggs, larval, juvenile, and adult) have different thermal sensitivity and will tend to reside or congregate in certain locations. The spatial and temporal distribution of thermally-sensitive stages will vary seasonally and this variability should be taken into account when planning for bioassessment work. The study design should identify the most sensitive species/life stages and locations and their seasonality so that the type or scale of thermal modeling provide useful thermal predictions in these critical areas (e.g., predicting both bottom and mid-water column temperatures). Identification of these critical areas and their seasonality may also reduce unnecessary effort in modeling where/when sensitive receptors are expected to be absent.

Recommended Best Practices: Identify microhabitats or areas of ecological importance potentially subject to thermal plume early in the study process to improve the focus and design of biological and surveys thermal monitoring and modeling. This information can support refinement of RIS selection, design of bioassessment endpoints (identification of most relevant temperature thresholds), and early recognition of areas where potential temperature exceedances are more likely to occur.

5.4.3 Long-term Monitoring Data

Site-specific long-term monitoring data on water temperature, climatic variations, biological resources, plant operations and discharge flows all provide information useful to many components of Section 316(a) demonstrations or thermal mixing studies. For example, this long-term data can be used:

- To demonstrate the absence of harm to a BIC over many years;
- To detect statistically-significant trends in temperature or biological communities;
- To calibrate and/or validate models; and
- To estimate seasonal or annual variation in ambient temperature in intake waters, or other uses.

Being able to rely on data sets collected over long periods of time should lead to greater confidence in overall results, while potentially reducing study program efforts and costs.

Unfortunately, long-term monitoring data are not equally available for all facilities. Extensive monitoring data are routinely available for nuclear-powered generation stations (i.e., QCNS, VYNPS) which have more prescriptive environmental monitoring requirements than non-nuclear plants. Power plants which have undergone several NPDES permit cycles should be able to use data collected in prior demonstrations or studies (e.g., VAPP). In the case of BPS, biological monitoring data were significantly augmented by extensive fishery work done by state resource agencies and academic institutions. In contrast, two of the case studies had limited monitoring information or lacked prior studies (e.g., BP, SJEC).

Recommended Best Practices: Inventory available historical site-specific monitoring data and prior study results. Check for potentially useable data from local or regional agencies, academic institutions or non-governmental organizations (NGOs) (e.g., watershed monitoring groups) but make sure that it can meet applicable regulatory quality assurance/quality control standards. Historical data should be checked to make sure that underlying conditions have not changed to such a degree that the data may not represent current conditions.

5.4.4 RIS Selection

Selection of RIS is an integral part of the 316(a) demonstration. The process typically starts with obtaining an inventory of fish, benthic or other aquatic life found in the waterbody of interest and ends with the selection of a set of appropriate important, local, or sensitive taxa for evaluation. A baseline field monitoring program to gather data for the RIS species selection may be necessary, depending on the availability and quality of current biotic data for a specific watershed (Bogardus, 1981).

RIS selection should consider important local habitats and the species likely to be found there. The scale and location of habitats considered for RIS selection in the case study examples of Section 5.3 varied greatly among the demonstrations. BP and VAPP provided a mostly descriptive evaluation of local bottom habitat conditions and communities (considered to be of poor quality) to justify excluding most benthic species as RIS. QCNS identified nine distinct Mississippi River habitats based on their location, depth, bottom material, and vegetation and mapped out important freshwater mussel beds (HDR 2009). VYNPS considered both the downstream ponded (lentic) and flowing (lotic) environments (NAI, 2004). On a much larger scale, BPS considered the entirety of MHB as its habitat of interest (EPA, 2002).

The number of RIS selected in the case studies varied among demonstrations and ranged from four species (QCNS) to over 20 (BPS). Sources of selected RIS included: species carried over from previous 316(a) demonstrations, species added at the request of resource agencies, species identified from new field surveys (BP), listed rare, threatened or endangered (RTE) species, or species projected from local adjacent habitats (SJEC). The majority of freshwater RIS were pelagic (open water) finfish with few benthic representatives or plant habitat formers.

Over the years, RIS selection has evolved from selection of a few common, easily surveyed species that approximately fit the RIS categories to more comprehensive consideration of trophic level functions, important habitat-formers, species interactions, indirect trophic effects, thermal sensitivity and protected species (e.g., QCNS, SJEC). Still, in many cases, the majority of "legacy" RIS from previous demonstrations were retained without comment, with resource agencies requesting additions of a few species (e.g., BP, VAPP, and VYNPS).

A more comprehensive ecological analysis does not necessarily result in a greater number of selected RIS, however. For example, QCNS identified nine local habitats, identified resident fish and evaluated potential long-term impacts to phytoplankton, zooplankton, ichthyoplankton, and benthic invertebrates (including mussels) (HDR 2009). Based on comparison of the density and diversity of biotic communities located in upstream, downstream and adjacent habitats and the apparent lack of harm (i.e., no significant differences in upstream-downstream profiles), they eliminated those communities from further evaluation. For selection of fish RIS, QCNS started with a master list of 93 species found in the identified habitats and then used screening criteria to winnow down to a set of 15 candidate indigenous species covering a range of trophic levels (HDR 2009). Despite this level of ecological detail, the RIS list was ultimately reduced to only four fish species, based on limited availability of detailed thermal tolerance data appropriate for their bioassessment methodology.

Recommended Best Practices: Consider, but do not rely upon, legacy RIS as a basis for species selection. The rationale for selecting RIS should be based on current biological surveys and habitat characteristics since environmental conditions may have significantly changed over time. RIS lists should include benthic communities, which are more susceptible to localized effects than pelagic finfish and have been largely ignored in previous demonstrations. General guidelines for RIS selection are provided in EPA (1977) or in state guidance (e.g., IDEM 2015). Updated approaches and guidance for selecting RIS are available as well as for updated sources of thermal tolerance data for additional numbers of taxa.[63]

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[63] Additional information on the basic RIS process (i.e., acquisition of local biotic data, determining appropriate species, stepwise refinement and selection of RIS) is discussed in several recent documents (e.g., Yoder et al., 2006;

5.4.5 Thermal Monitoring

Thermal monitoring and plume surveys provide field measurements of temperature as data input to calibrate and validate thermal mixing models. Thermal monitoring was conducted in all case studies but differed greatly in terms of scale, seasonality and methodology. Thermal monitoring methods, equipment and data collection and management have greatly improved over the last 20 years and *in-situ* or remote sensing options are available (see Section 4.2). These improvements greatly enhance the ability of permit applicants to collect large amounts of spatial, multi-depth and temporally-distributed temperature data quickly and cost-effectively.

Five of the case studies[64] employed a variety of temperature measurement methods and field study designs:

- BP – combination of 13 moored thermistor arrays and multiple boat-based survey cruises; thermal model input data primarily collected over single summer period (2010).
- BPS – combination of moored thermistor arrays, surveys cruises, aerial and satellite infrared imagery; thermal model input data collected over several years and season (1995-1998).
- QCNS – combination of survey cruises and aerial infrared imagery; thermal model input data collected primarily over single year (2003).
- VAPP – set of 25 moored thermistor and water quality sampling stations; thermal model input data collected over several years (1995-2002).
- VYNPS – continuous water temperature at upstream (Station 7) and downstream (Station 3) monitoring locations; thermal model input data collected over several years (1998-2002).

The precise combination of methods and equipment proposed during study design is usually dictated by the thermal complexity of the receiving waters and/or location of sensitive habitats.

<u>Recommended Best Practices</u>: Design the thermal monitoring study to use an integrated mixture of equipment and methods such as moored thermistor arrays with data loggers for ambient and local conditions, survey cruises to plot thermal plume during periods of expected thermal stress, and remote TIR imagery (hand-held, drone, aerial, satellite) to provide “snapshots” of thermal conditions over local and regional areas.

The thermal monitoring duration should be sufficiently long and detailed to provide reliable estimates of seasonal and annual variance for comparison to historical data or as input to thermal modeling scenarios. Reliance on monitoring over a few weeks or single season for calibration and verification may produce a biased result depending on the representativeness of the period to long-term conditions. Data collection over several years, while desirable, may or may not capture extreme events and is expensive and time-consuming with regard to permit review. Data collection over multiple seasons

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Yoder 2012, and IDEM 2015). In addition, EPA has developed temperature tolerance information to support selection of RIS in four geographic regions – Middle Atlantic, Great Lakes, Inland Great Lakes and Pacific Northwest (see Sections 3.2 through 3.5).

[64] No water temperature monitoring was conducted for SJEC, as it would discharge into a waterbody that was previously ephemeral and would not have any substantial flow or temperature data.

within a year, combined with modeling extrapolations for extreme conditions, may be a pragmatic and acceptable approach for many facilities.

5.4.6 Selection of Thermal Mixing Models

A number of hydrothermal models are available for use in Section 316(a) demonstrations or thermal mixing zone studies (see Section 4.1). The following thermal mixing models[65] were used in the case studies:

- BP – CORMIX for near-field and EFDC (3-D) for far-field.
- BPS – CORMIX for near-field and WQMAP/WASP for far-field.
- QCNS – CFD (3-D).
- SJEC – HY-8 and HEC-RAS.[66]
- VAPP – ECOMSED (3-D).
- VYNPS – BFHYDRO (3-D)

Each of the models were calibrated to site-specific monitoring data and provided predictions regarding plume location and water temperatures appropriate for the bioassessment of RIS. The use of 3-D models may be required when bottom-dwelling RIS are used or the receiving water is subject to stratification. Near-field plume models may be required to characterize initial dilution and plume formation.

Recommended Best Practices: Overall, the selection of a model is usually based on its capability to assess the impact, usage in prior 316(a) demonstration, ease of application or degree of modeling expertise, degree of effort and cost, and best professional judgment. Non-proprietary models should be used when feasible to assess the site-specific conditions of the facility (EPA, 2009). Permit applicants should submit a model development plan to regulatory authorities for review prior to beginning work on model development and assessment.

5.4.7 Thermal Modeling Scenarios

Thermal models should evaluate a wide range of temperature and flow conditions including existing and proposed changes in the discharge volume and temperature and several combinations of potential ambient temperature and flow of the receiving water. To evaluate the range of conditions, a number of both historical and hypothetical scenarios should be tested. The case studies varied in the number and complexity of scenarios tested, ranging from:

- BP – maximum permitted monthly discharge under existing and proposed operations under spring and summer ambient conditions, varying wind direction, and nearshore current direction.

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[65] See individual case studies for model acronym definitions. Listing of these models should not be construed as implicit approval or recommendation by EPA for use in Section 316(a) demonstrations. Nor is Section 4.1 intended to be an exhaustive list of available temperature models.

[66] The analysis for SJEC used flow modeling (not thermal modeling) and a statistical relationship to predict water temperatures downstream of the discharge. While not as complex as the modeling at the other facilities, this approach worked well for the SJEC scenario. As a new facility with a comparatively small discharge flow into a waterbody that will be effluent dominated, a more complex model was not necessary.

- BPS – historical and hypothetical scenarios evaluating the effects of reduced thermal discharges incorporating a cooling tower (i.e., enhanced multi-mode operation) or no discharge.
- QCNS – simulated facility operations at maximum power over a series of relatively low Mississippi River flows.
- SJEC – used a simpler approach to construct a predictive model for downstream temperatures.
- VAPP – two plant heat load scenarios ("Average Conditions" and "Upper Bound Conditions").
- VYNPS – station's thermal plume under existing conditions and proposed summer thermal discharge limits.

BP and QCNS incorporated more environmental variability of ambient conditions into the model scenarios. However, in general, climate change and its influence in potentially altering the distribution, frequency and magnitude of precipitation events and resulting river flows or water storage was not well addressed by most studies.

Recommended Best Practices: Non-proprietary models should be used when feasible to assess the site-specific conditions of the facility (EPA 2009). A combination of near-field and far-field models should be considered, capturing both initial plume formation and larger scale mixing and heat budget simulation. Use of simpler models that treat temperature as a conservative tracer may be less reliable except in near-field applications.

The thermal model should be run over a range of plant operation conditions. At a minimum, these conditions should include discharge under existing permit and proposed ATELs under average and maximum permitted flow conditions, along with other applicable plant flows (various generating unit combinations). Receiving water ambient temperature should provide an adequate range of expected seasonal levels, with particular emphasis on periods of maximal thermal stress to ecological receptors due to warm temperatures, low flows, or a combination of both. Other environmental variables, such as the range of local current speed (low, high), wind speed and direction, wave and tidal range, and presence of vertical stratification (thermal and salinity), may be important for modeling on a site-specific basis. For consideration of future conditions, the thermal modeling effort should include assessments of climate change impacts on flows and ambient temperatures. Finally, every step of the model development process including data selection, calibration, verification, and suite of appropriate model scenarios should be described in detail and fully documented.

5.4.8 Bioassessment

Bioassessment provides the critical evaluation of whether the existing or proposed thermal discharge has harmed or has the potential to harm the local BIC. The case studies took several different approaches but most combined:

- Assessment of the status of ecological communities (fish, benthos, plants) inside and outside of thermal plume influence and
- A species-specific biothermal assessment using predicted water temperatures (typically under "worst-case" conditions, usually maximum heat output or flow discharge in late summer when water levels are typically lowest) to thermal tolerance thresholds of the RIS.

In cases where thresholds were exceeded, the duration and location were calculated as well as estimates of the percentage of the total habitat affected (i.e., habitat exclusion). These generally are the basis for assessment of evidence of harm to the BIC.

The community assessment methodology included comparison of biological metrics (BP), community assemblages (QCNS), and statistical comparison of long-term biological data (VYNPS). BPS used a weight-of-evidence approach to establish a causal relationship between historical changes in thermal output and declines of several flatfish species in MHB (EPA, 2002). This analysis differed from the others in that it evaluated the positive effect of reducing existing facility discharge flows instead of the impact of continuing or increasing them.

Thermal endpoints used in the biothermal assessment included thermal avoidance (e.g., zone of passage restrictions, habitat exclusion), adverse impacts on reproduction, spawning or growth, and chronic and acute mortality (including heat and cold shock). Several studies considered the role of acclimation[67] in mitigating temperature thresholds. Summarization of biothermal results included tabular comparison of maximum predicted water temperature to the most stringent thermal endpoints among RIS (BP, SJEC), construction of species-specific temperature tolerance polygons (QCNS), and evaluation of endpoint relative to RIS life stages (VAPP). Other biothermal assessment methods are available.

Recommended Best Practices: The case studies contain alternative methods to demonstrate a lack of harm to the BIC. Biothermal assessment of RIS via comparison of predicted water temperatures to thermal thresholds is an acceptable way to demonstrate lack of harm to the local BIC. However, if conducted, bioassessment should not be limited to consideration of RIS adult stage mortality endpoints but should include considerations of vulnerable life stages, critical habitat locations, and migratory patterns. Comparison of community characteristics in habitat areas inside and outside the influence of the thermal plume provides good support to the RIS temperature threshold approach. Some of these methods are more applicable for use with long-term biological monitoring data that may not be available for all facilities.

5.4.9 Section 5.4 Select General References

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[67] Acclimation is the process in which an individual organism adjusts to a gradual change in its environment (such as a change in temperature, humidity, photoperiod, or pH), allowing it to maintain performance across a range of environmental conditions.

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