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**Modeling Regulatory Curtailments at Power Plants with Once-through Cooling**

This document describes a new method of estimating power plant curtailments equipped with once-through cooling due to regulatory limits. It combines two equations, a thermal mixing equation and a power plant discharge equation, to accurately capture the enforcement of environmental regulations.

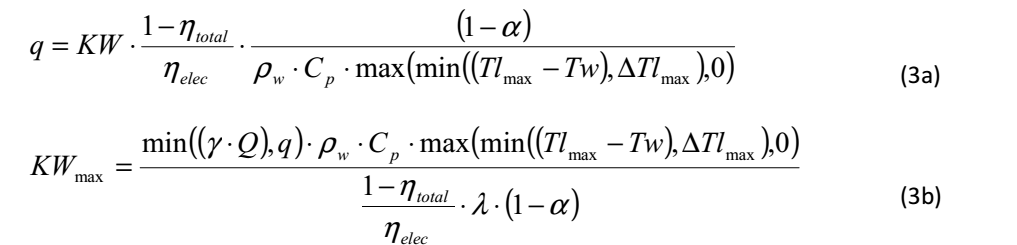
Power plants with once-through cooling discharge large volumes of heated water into rivers, lakes, and other bodies of water. These discharges are limited by environmental regulations. Specifically, there are two types of environmental regulations: 1) limits on the temperature of the river downstream of the discharge, and 2) limits on the increase in temperature of the river downstream of the discharge.

These limits vary state by state, as well as plant by plant. Limits on a plant-specific basis are set out in NPDES permits for each plant. I have reviewed the NPDES permits for 13 power plants, mainly coal plants, in North Carolina (NC) in order to obtain a detailed understanding of the limits plants actually need to comply with. The state-level regulation in NC limits stream temperatures to 32C and limits the increase in stream temperatures to 2.8C. However, limits established in NPDES permits for several coal plants in NC exceed these regulatory limits by several degrees. Also of note, these regulatory limits are applied at the end of a “mixing zone” for most plants, which range from 2-12 miles. Thus, while state-level regulations provide a rough approximation of regulations faced by power plants, in some cases power plants are permitted to exceed state limits. Furthermore, these state limits do not apply to the discharge from power plants or to the river temperature at the point of discharge, but rather once mixing has occurred.

Here, we develop a set of equations that can be used to limit discharges based on the temperature of the river once mixed with discharges from power plants. First, I will discuss a set of equations previously used by van Vliet et al., and why these equations do not capture the dynamics I aim to capture.

**Van Vliet Equations**

Equations 3a and 3b below are used by van Vliet et al. to estimate curtailments for power plants with once-through cooling due to environmental regulations.



where λ, ηtotal, ηeff, Cp, ρ, α, and γ are constants; KW is installed capacity; q is water withdrawal and discharge by a power plant; Tlmax and ΔTlmax are regulatory stream temperature limits; KWmax is the maximum achievable capacity; and Tw is the simulated daily water temperature at the power plant location.

Per equation 3a, if Tlmax > Tw, then power plant capacity equals zero, as expected. Stream temperatures already exceed the regulatory limit, so the power plant cannot discharge into the stream, hence it must shut off.

However, if Tw < Tlmax, as Tw approaches Tlmax, then q goes to infinity. Note that this occurs only because Tl­max is directly limiting q in equation 3a. If Tlmax, the stream regulatory limit, was not enforced on q, then q would not need to go to infinity as Tw approaches Tlmax. Indeed, while the text states that Tlmax is a stream regulatory limit, it appears that Tlmax serves as a hard constraint on the temperature of discharges from the power plant – not of the mixed stream temperature – in 3a. As q goes to infinity, then equation 3b will result in curtailments, as the first min() expression will result in discharges being limited to γ\*Q. Thus, the power plant will be curtailed. However, this curtailment is being driven by the application of Tlmax to the discharge temperature rather than to the mixed downstream stream temperature.

**Proposed Equations**

In order to correct for this issue and apply regulatory limits to the mixed stream temperature (note that mixing zones, as discussed above, stretch 2-12 miles for most power plants), I combine two equations – a thermal mixing equation and a power plant discharge equation – to calculate the mixed stream temperature given a power plant discharge. An iterative procedure can then be used to determine what the maximum thermal discharge, and therefore power output level, from a power plant is in order to comply with regulatory limits per the mixed stream temperature.

The first equation is a simple thermal balance equation:

(Eqn. 1)

where Tx is the mixed stream temperature; mg is the flow of the power plant discharge; mr is the flow of the river; Tr is the upstream stream temperature, or stream temperature in that cell; Tg is the temperature of the power plant discharge, which equals Tr + ΔTg; and ΔTg is the increase in temperature of cooling water through the condenser, which is a condenser design variable. Thus, equation 1 provides the mixed stream temperature given thermal input from a power plant.

The second equation is similar to equation 3a from van Vliet. It estimates the discharge flow from a power plant taking ΔTg as a design variable at the condenser.

(Eqn. 2)

where is the net plant efficiency, which equals 3.412 divided by the plant net heat rate; kos is the fraction of waste heat lost to other heat sinks, which equals 12% for coal-fired plants and 20% for gas-fired plants per Bartos and Chester; p is the power output of the power plant; and γ indicates the maximum fraction of the river flow that can be extracted for cooling purposes. Note that the main difference between my eqn. 2 and van Vliet’s eqn. 3a is that discharges are not strictly limited by environmental regulations in eqn. 2. Rather, I assume a constant temperature change of the cooling water across the condenser, and use that value plus the desired power output to determine what mass flow would be required.

(Note that our assumption of a constant temperature change is a simplification. On very hot summer days, the condenser may not be able to achieve its designed temperature change, requiring a greater intake. With that said, power plant owners design condensers to function during hot summer days, so the decrease in the temperature change across the condenser during the hottest summer days should be not be significant. Nonetheless, accounting for such cases is relatively straightforward via sensitivity analysis by assuming only a fractional decrease in the temperature change across the condenser occurs per degree above a given threshold.)

Inserting eqn. 2 into eqn. 1 yields the following equation for the mixed stream temperature given the power output at a power plant and its condenser design:

(Eqn. 3)

Note that eqn. 3 does not explicitly account for environmental limits. However, given a mixed stream temperature, I can compare that to the regulatory limit and determine whether the power plant needs to be curtailed. Specifically, for each power plant, I can test a range of power output values between 0 and its maximum capacity and determine the maximum potential power output before mixed stream temperatures exceed regulatory limits. The same approach can be applied in conjunction with the upriver stream temperature to capture regulatory limits on the change in water temperatures.

**Numerical Example Comparing Outcomes with My Equations to van Vliet et al.’s Equations**

In order to demonstrate the difference between my equations and those from van Vliet et al., I have run a simple numerical example using the following parameters:

Table 1: Parameters used in numerical analysis.

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Value** | **Units** |
| η | 0.3412 |  |
| ρ | 1 | g/cm3 |
| Cp | 4.184 | J/gC |
| ΔT | 20 | C |
| γ | 0.3 |  |
| kos | 0.12 |  |
| Tr | 31.8 | C |
| Tlmax | 32 | C |
| mr | 1000 | m3/s |

The table below provides the results from my equations for varying power output levels at a 1,000 MW nameplate capacity coal-fired power plant. Note that p equals power output; q equals required water withdrawal and discharge based on the power output; mg equals water withdrawals and discharge by the power plant, or min(γ\*mr,q); and Tx is the downstream stream temperature after mixing. Red cells indicate prohibited power output levels because Tx exceeds the regulatory limit, Tlmax (32 C). Green cells indicate allowed power output levels. Thus, my equations indicate the power plant could produce power up to 548 MW without exceeding regulatory limits.

|  |  |  |  |
| --- | --- | --- | --- |
| **p (MW)** | **q (m3/s)** | **mg (m3/s)** | **Tx (C)** |
| 1000 | 19 | 19 | 32.17 |
| 549 | 10 | 10 | 32.01 |
| 548 | 10 | 10 | 32.00 |
| 500 | 9 | 9 | 31.99 |
| 400 | 8 | 8 | 31.95 |
| 300 | 6 | 6 | 31.91 |
| 200 | 4 | 4 | 31.88 |
| 100 | 2 | 2 | 31.84 |
| 0 | 0 | 0 | 31.80 |

Conversely, using Eqns. (3a) and (3b) from van Vliet, the maximum allowable capacity is 159 MW. The table below explains why such strong curtailments occur. Due to the small difference between Tr (31.8 C) and Tlmax (32 C), water withdrawals as calculated by Equation (3a) are significantly higher than in the table above. Consequently, the power plant is prohibited from withdrawing that required volume of water, and is instead constrained to γ\*mr, resulting in curtailments.

|  |  |  |
| --- | --- | --- |
| **p (MW)** | **q (m3/s)** | **mg (m3/s)** |
| 1000 | 1887 | 300 |
| 549 | 1036 | 300 |
| 548 | 1034 | 300 |
| 500 | 944 | 300 |
| 400 | 755 | 300 |
| 300 | 566 | 300 |
| 160 | 302 | 300 |
| 159 | 300 | 300 |
| 100 | 189 | 189 |
| 0 | 0 | 0 |