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Assessing the impacts of droughts and heat waves at thermoelectric power plants in the United States using integrated regression, thermodynamic, and climate models

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ABSTRACT

Recent droughts and heat waves have revealed the vulnerability of some power plants to effects from higher temperature intake water for cooling. In this evaluation, we develop a methodology for predicting whether power plants are at risk of violating thermal pollution limits. We begin by developing a regression model of average monthly intake temperatures for open loop and recirculating cooling pond systems. We then integrate that information into a thermodynamic model of energy flows within each power plant to determine the change in cooling water temperature that occurs at each plant and the relationship of that water temperature to other plants in the river system. We use these models together with climate change models to estimate the monthly effluent temperature at twenty-six power plants in the Upper Mississippi River Basin and Texas between 2015 and 2035 to predict which ones are at risk of reaching thermal pollution limits. The intake model shows that two plants could face elevated intake temperatures between 2015 and 2035 compared to the 2010–2013 baseline. In general, a rise in ambient cooling water temperature of 1 °C could cause a drop in power output of 0.15%–0.5%. The energy balance shows that twelve plants might exceed state summer effluent limits.

1. Introduction

Power plants withdraw a significant amount of water – about 45% of total fresh and saline water withdrawals in the country in 2010 – to cool steam used to generate electricity (Maupin et al., 0000). At the same time, ongoing drought has revealed the vulnerability of thermoelectric power plants to the risks of low water levels and high water temperatures. High temperatures can cause the cooling process to become less efficient. In general, a rise in ambient cooling water temperature of 1 °C could cause a drop in power output of 0.15–0.5% (Asian Development Bank, 2012; Linnerud et al., 2011).

In an open-loop or recirculating cooling power plant with a cooling pond, the relationship between a power plant's efficiency, thermal loading, and cooling water characteristics are determined by thermodynamic principles. As water passes through the power plant, heat is lost to the air or transferred to the cooling water and into the pond, river, or lake as the water is discharged. For the plant to condense the same amount of steam in the cooling process when the intake water temperatures are higher, it needs to withdraw water at higher rates, heat the withdrawn water to higher temperatures, or both. If the power plant is at risk of violating its thermal water discharge limits in its environmental permit, the net power generation can be reduced as a way to lower discharge temperatures. This risk to loss of generation is important because it affects the reliability of the power system and puts human lives at risk. This risk can be exacerbated in the future, as decisions are made today about long-lived capital assets that might be operating under different climatic conditions in the future. Therefore, analysis and methods presented in this paper can be used to inform those decisions with the intent of improving the reliability of current and future power sector.

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1.1. Power plant cooling

Thermoelectric power plants generally require water as the working fluid as part of the steam cycle that is used to generate power (Moran and Shapiro, 2004). However, the largest demand for water in thermoelectric plants is for the cooling water used in condensing the steam back into a usable working fluid (Wagman, 2013). Several types of cooling are used. The most common types are once-through and recirculating cooling. Once-through plants withdraw large amounts of water from rivers, lakes, ponds, and groundwater wells and pass it through tubes of a condenser to cool the steam as it exits the turbine. The steam is then returned to the boiler as liquid water for use again. The cooling water then returns to the environment at an elevated temperature (Moran and Shapiro, 2004). Wet-recirculating systems use cooling towers or cooling ponds to dissipate heat from cooling water to the atmosphere, reusing the cooling water multiple times in the process (Mittal and Gaffigan, 2009). This study examines once-through and recirculating cooling plants with cooling ponds because these plants return cooling water to the environment at elevated temperatures.

1.2. Previous research on water constraints for power plants

In recent years, there have been many assessments of water use for power as well as advancements in evaluating the impacts of water stress and increased energy and water demand on the power sector (Yan et al., 2013; Koch and Vogele, 2009; Miara and Vorosmarty, 2013; Stillwell et al., 2011; Roy et al., 2012; Sovacool and Sovacool, 2009; Chandel et al., 2011; Harto et al., 0000; Fthenakis and Kim, 2010; Feeley et al., 2008; Vassolo and Doll, 2005). Given that climate projections estimate higher air temperatures for the United States in future years (PNNL, 0000; IPCC, 0000), many of these assessments seek to evaluate the power plant productivity in the face of low water levels or high air or water temperatures (Yan et al., 2013; Scanlon et al., 2013). A National Energy Technology Laboratory report found that most cases of de-rating or shutdown were not associated with low water levels at the intake but rather elevated temperatures of effluent or at cooling water intakes (NETL, 2010). Miara and Vorosmarty model power plant thermal discharges into riverine systems in the Northeastern US (Miara and Vorosmarty, 2013). While the work presented here is similar to Miara and Vorosmarty in seeking to characterize impacts of discharges into a large riverine system as well as cooling ponds, the analysis in this manuscript is taken at a screening level and includes a thermodynamic model of the power plant itself with the intent of informing decisions in the power sector. By contrast, the study by Miara and Vorosmarty includes much more hydrological detail to quantify impacts on the water systems.

Many studies have assessed the impacts of low water levels, but few have attempted to quantify the vulnerability power plants face of reduced generation associated with higher cooling water temperatures. Building on past research in the field (Yan et al., 2013; Koch and Vogele, 2009; Miara and Vorosmarty, 2013; Stillwell et al., 2011; Roy et al., 2012; Sovacool and Sovacool, 2009; Chandel et al., 2011; Harto et al., 0000; Scanlon et al., 2013; Cook et al., 2013, 2014; Sanders, 2015) as well as work in surface water temperature modeling (Segura et al., 2015; Webb et al., 2008; Komatsua et al., 2007; Stefan et al., 1993; Webb and Walling, 1993; Erickson and Stefan, 1996; Webb and Nobilis, 1997; Pilgrim et al., 1998; Ozaki et al., 2003; Ducharne, 2008; Caldwell et al., 2014), this research seeks to fill the gap in knowledge of the magnitude of influence that higher temperatures will have on power plant effluent water temperatures to quantify a power plant's exposure to risk of de-rating induced by warm cooling water in future decades. This study assesses the effect of meteorological parameters and heat dissipated from power plant cooling to determine the change in water temperature at various power plants in the Upper Mississippi River Basin (UMRB) and the Gulf Coast Basin (GCB) by employing multiple linear regression and energy balances and taking into account the effect the performance of a neighboring upstream plant could have on downstream plants. The risk of reduced operations is assessed through estimation of intake and effluent water temperatures over the next 1–2 decades and comparison to current restrictions.

2. Material and methods

To analyze the risk of power plant curtailment due to high effluent discharge temperatures, a multiple linear regression model for intake cooling water temperature in combination with an energy balance of the power plant is utilized to estimate the historical cooling water effluent temperatures (T_{eff}) at power plants in the UMRB and GCB. This model is executed for power plants that reported discharge temperatures and utilized an open loop or recirculating cooling pond system. The model employs proxies for the influence of cooling water intake temperature and heat dissipated in electricity generation, the details of which are explained below.

2.1. Calculation of intake temperature via multiple linear regression

Past research in modeling monthly surface water temperature has indicated a correlation between air temperature and surface water temperature in streams and lakes (Segura et al., 2015; Webb et al., 2008; Webb and Walling, 1993; Erickson and Stefan, 1996; Webb and Nobilis, 1997; Pilgrim et al., 1998; Ozaki et al., 2003; Ducharne, 2008; Caldwell et al., 2014). Segura et al. reviewed nineteen stream water temperature models conducted between 1982 and 2014, sixteen of which employed linear or combined linear/logistic models for water temperature (Segura et al., 2015).

In this study, we use a multiple regression model to estimate monthly average cooling water intake temperature at month, t, with ambient dry bulb air temperature ($T_{DB}(t)$ (°C)), dew point ($T_{DP}(t)$ (°C)), intake temperature of the previous month ($T_{in}(t-1)$ (°C)), average wind speed for the month ($V(t)$ (m/s)), and temperature of the cooling water discharged from the upstream plant ($T_{up}(t)$ (°C)). Note that t represents the time in months while the t-test is a hypothesis test. A regression is employed based on characteristics of the environment around each power plant and historical data from 2010–2013 to determine the five parameter coefficients, $\beta_1 - \beta_5$, and constant β_0. The resulting model for estimated power plant cooling water intake temperature, $T_{in}(t)$, is shown in Eq. (1). While the equation is the same for each power plant, the estimates for $\beta_0 - \beta_5$ are specific to each power plant tested. The illustration in Fig. 1 shows the relationship between $T_{in}(t)$, $T_{up}(t)$, and the plant's effluent temperatures, $T_{eff}(t)$.

$$T_{in}(t) = \beta_5 T_{DB}(t) + \beta_4 V(t) + \beta_3 T_{DP}(t) + \beta_2 T_{in}(t-1) + \beta_1 T_{up}(t) + \beta_0. \quad (1)$$

Argonne and PNNL used weather station data to calculate historical average monthly air temperature, dew point, and wind speed used in Eq. (1). The average values for each month were calculated based on interpolated daily values measured by National Oceanic and Atmospheric Administration climate stations. The interpolation was done using a quadrat method, where daily climate data were aggregated first to a grid of points across the entire basin (known as a HUC2), then grid point daily values were aggregated by weighted average to subbasins (known as HUC8 subbasins). Once Grid Cell daily values were interpolated, daily data was then combined to HUC8 scale using a weighted

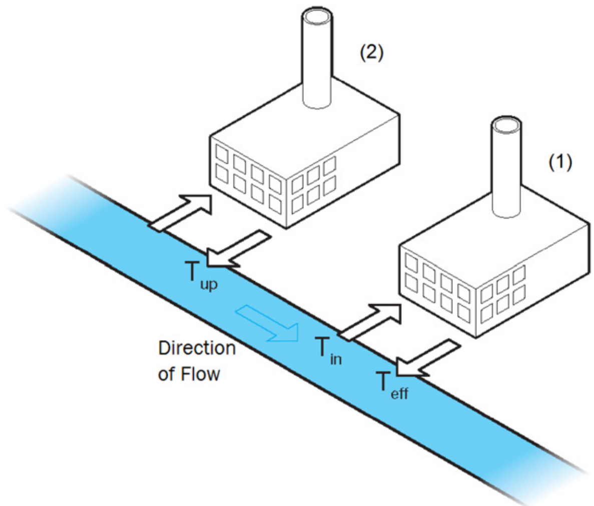

Fig. 1. The illustration shows two plants, a downstream plant (1) and an upstream plant (2), and the relationship between the temperature of the water pulled into the downstream plant for cooling ($T_{in}(t)$), the temperature of the cooling water as it is discharged from the downstream plant ($T_{eff}(t)$), and the temperature of the cooling water discharged from the upstream plant ($T_{up}(t)$). The upstream plant's discharge temperature could affect intake temperature of the downstream plant.

average of the daily values from the grid cells. Monthly averages were taken of daily data.

Argonne and PNNL also calculated future values of monthly air temperature, dew point, and wind speed. Average monthly temperatures were calculated based on hourly air temperature from a Regional Earth System Model (RESM) output and corrected with bias correction. Average monthly dew point temperatures were calculated based on daily dew point temperature from the RESM output. The dew point temperatures were estimated from bias-corrected air temperature, raw relative humidity data, and raw surface pressure data by the PNNL team. Average wind speed was calculated based on daily value of wind vector components.

Historical intake and effluent temperatures data were extracted from the Energy Information Administration (EIA) form 923 and the Environmental Protection Agency (US EPA, 2012; US EIA, 2015). Only twenty-six power plants using open-loop and closed-loop cooling ponds have sufficient data to perform our regression and rate-based energy analyses. The plants of interest are shown in Fig. 2 and in Table 1. The availability of data also restricted the period of time that the models could estimate to 2010–2013.

2.2. Calculation of the change in temperature at the plant via energy balance

A rate-based energy balance is used to estimate the increase in cooling water effluent temperature relative to the influent temperature that occurs within the power plant condenser. It is assumed that the power plant is operating at quasi steady state, meaning the power plant is not accumulating energy. Energy leaves the power plant at the same rate energy enters, as shown in Eq. (2) where $\dot{E}_{in}$ is all energy flows into the power plant and $\dot{E}_{out}$ is all energy flows leaving the power plant.

$$\Sigma \dot{E}_{in} = \Sigma \dot{E}_{out}. \tag{2}$$

The control volume drawn to estimate the energy balance of a typical once-through power plant is shown in Fig. 3. The energy flows into and out of the system are represented in the figure and in Eq. (3) using the rate of energy input via fuel ($\dot{E}_{chemical,in}(t)$), the rate of energy output via electricity ($\dot{E}_{electricity,out}(t)$ (MW)), the rate of energy flow into the plant via withdrawn cooling water ($\dot{E}_{cw,in}(t)$), the rate of energy flow out of the plant via cooling water effluent ($\dot{E}_{cw,eff}(t)$), the rate of energy flow out of the plant via evaporated cooling water ($\dot{E}_{cw,evap}(t)$), the rate of energy flow into the plant in the air ($\dot{E}_{air,in}(t)$), the rate of energy flow out of the plant through the stack ($\dot{E}_{stack,out}(t)$), and other net energy losses at the plant such as unspent fuel and radiation to the environment ($\dot{E}_{other,out}$). The model is based on an energy balance found in Masters (2004). Applying the quasi-steady state assumption, Eq. (3) shows that the energy flows into the plant are equivalent to the energy flows out of the plant.

It is also possible to use the waste heat from power generation for district heating. This option is not included in the analysis; thus, it has been left out of Fig. 3. However, district heating is generally considered a beneficial use of waste heat.

$$\begin{aligned}\dot{E}_{chemical,in}(t) + \dot{E}_{air,in}(t) + \dot{E}_{cw,in}(t) \\ = \dot{E}_{electricity,out}(t) + \dot{E}_{stack,out}(t) + \dot{E}_{other,out}(t) \\ + \dot{E}_{cw,eff}(t) + \dot{E}_{cw,evap}(t).\end{aligned} \tag{3}$$

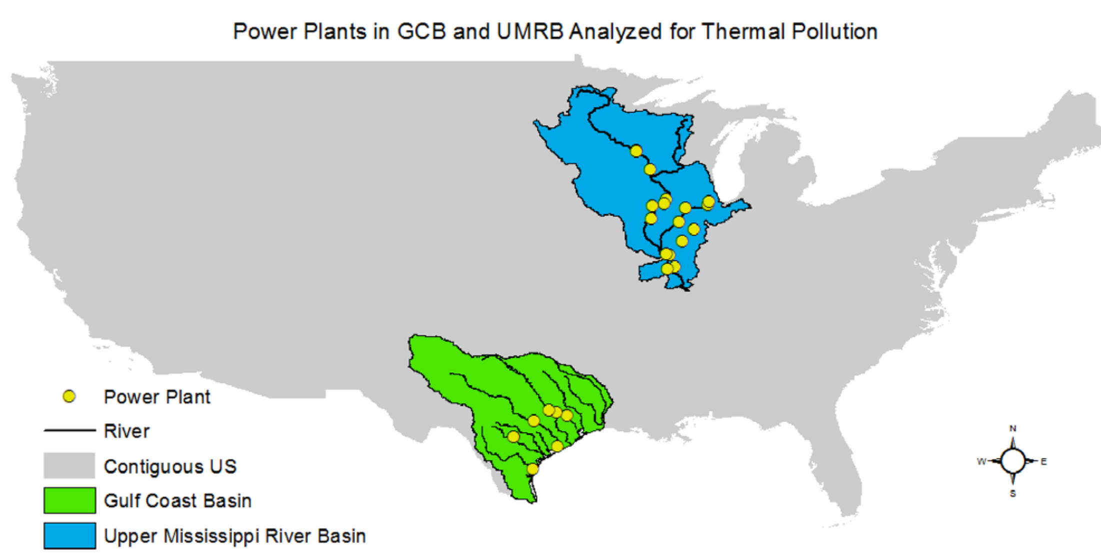

Fig. 2. Intake and effluent temperatures at twenty-six plants in the GCB and the UMRB were modeled based on historical temperatures to estimate potential for issues in the future.

Table 1
The table includes the ID, name, state, energy source, nameplate capacity, and cooling water source for the plants included in this study. The abbreviation "NG" represents natural gas and "DFO" represents distillate fuel oil. The information is available in US EIA (2015).

Plant ID	Plant name	State	Energy source	Capacity (MW)	Water source
204	Clinton	IL	Nuclear	1138.3	Salt Creek
856	E.D. Edwards	IL	Coal	136.0	Illinois River
874	Joliet 9	IL	Coal	360.4	Desplaines River
876	Kincaid	IL	Coal/NG	659.5	Sangchris Lake
880	Quad Cities	IL	Nuclear	1009.3	Mississippi River
884	Will County	IL	Coal/DFO	299.2	Chicago Sanitary and Ship
889	Baldwin Energy Complex	IL	Coal/DFO	625.1	Baldwin Lake/Kaskaskia River
892	Hennepin Power Station	IL	Coal/NG	306.3	Illinois River
898	Wood River	IL	Coal/NG	112.5	Mississippi River
1047	Lansing	IA	Coal	37.5	Mississippi River
1081	Riverside	IA	Coal/NG	141.0	Mississippi River
1104	Burlington	IA	Coal/NG	212.0	Mississippi River
1167	Muscatine	IA	Coal/NG	25.0	Mississippi River
2107	Sioux	MO	Coal/DFO	549.7	Mississippi River
3457	Lewis Creek	TX	NG	542.8	Lewis Creek Reservoir
3601	Sim Gideon	TX	NG	144.0	Lake Bastrop
3611	O.W. Sommers	TX	NG/DFO	446.0	San AntonioRiver
4140	Alma	WI	Coal	136.0	Mississippi River
4271	John P. Madgett	WI	Coal	387.0	Mississippi River
4939	Barney M. Davis	TX	NG	1082.2	Laguna Madre
6136	Gibbons Creek	TX	Coal	453.5	Gibbons Creek
6155	Rush Island	MO	Coal/DFO	621.0	Mississippi River
6181	J.T. Deely	TX	Coal/NG	486.0	San Antonio River
6243	Dansby	TX	NG/DFO	105.0	Lake Bryan
6251	South Texas Project	TX	Nuclear	2708.6	Colorado River
7097	J.K. Spruce	TX	Coal/NG	566.0	San Antonio River

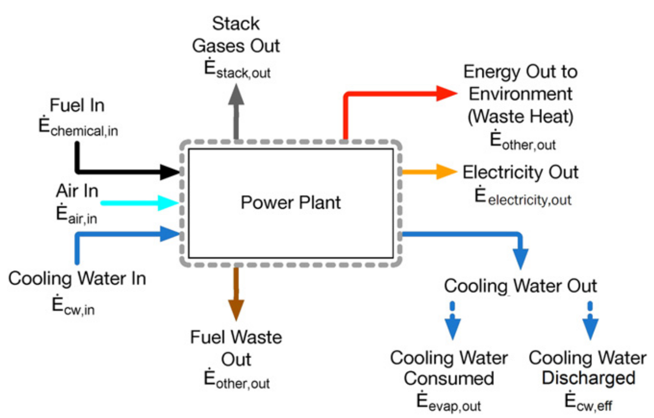

Fig. 3. The control volume around a typical once-through cooling power plant and the energy movement across that boundary are shown. The energy balance for this control volume is shown in Eq. (3).

A rate-based mass balance is then used to estimate the cooling water entering and leaving the plant. Under the steady state assumption, it is also assumed the power plant is not accumulating water, and the cooling water leaves the power plant at the same rate that it enters the plant. Expanding that equation, $\dot{m}_{cw,in}(t)$ (kg/s) is the mass flow rate of the cooling water into the plant, $\dot{m}_{cw,eff}(t)$ (kg/s) is the mass flow rate of the cooling water out of the plant, and $\dot{m}_{cw,evap}(t)$ (kg/s) is the mass flow rate of the cooling water consumed. It is assumed the cooling water consumption reported by each power plant to the EIA is evaporation.

$$\Sigma\dot{m}_{cw,in}(t) = \Sigma\dot{m}_{cw,out}(t) \tag{4}$$

$$\dot{m}_{cw,in}(t) = \dot{m}_{cw,eff}(t) + \dot{m}_{cw,evap}(t). \tag{5}$$

The energy entering and leaving the plant via the cooling water is determined using Eqs. (6)–(8) using the temperature of the cooling water ($T_{in}(t)$ or $T_{eff}(t)$ (°C)), the enthalpy of vaporization ($h_{vap}(t)$ (kJ/kg)), and the specific heat of water (C_{cw} (kJ/kg- °C)).

$$\dot{E}_{cw,in}(t) = \dot{m}_{cw,in}(t) \times C_{cw} \times T_{in}(t) \tag{6}$$

$$\dot{E}_{cw,eff}(t) = \dot{m}_{cw,eff}(t) \times C_{cw} \times T_{eff}(t) \tag{7}$$

$$\dot{E}_{cw,evap}(t) = \dot{m}_{cw,evap}(t) \times h_{vap}. \tag{8}$$

Substituting Eqs. (6)–(8) into Eq. (3) yields Eq. (9).

$$0 = \dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t) + \dot{E}_{air,in}(t) - \dot{E}_{stack,out}(t) - \dot{E}_{other,out}(t) + \dot{m}_{cw,in}(t) \times C_{cw} \times T_{in}(t) - \dot{m}_{cw,eff}(t) \times C_{cw} \times T_{eff}(t) - \dot{m}_{cw,evap}(t) \times h_{vap}. \tag{9}$$

The rate of energy flow into the plant via air, the rate of energy flow out of the plant through the stack, and the other net energy losses at the plant such as unburned chemical fuels or unreacted nuclear fuels and energy shedding to the environment could be determined in a similar fashion to the energy flow via cooling water. However, these flows are estimated as ratios of the energy flow out of the plant using Eqs. (10), (11), and (12) where R is, respectively, the ratio of air into the plant, the stack gases out of the plant, and other energy losses relative to total energy into and out of the plant.

$$R_{air,in} = \frac{\dot{E}_{air,in}}{\dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t)} \tag{10}$$

$$R_{stack,out} = \frac{\dot{E}_{stack,out}}{\dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t)} \tag{11}$$

$$R_{other,out} = \frac{\dot{E}_{other,out}}{\dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t)}. \tag{12}$$

The combined ratio of rate of energy losses at the plant compared to the total energy flows into and out of the plant is shown in Eq. (13). Estimated values for $R_{combined}$ are included in B.5 in Appendix B.

$$R_{combined} = R_{stack,out} + R_{other,out} - R_{air,in}. \tag{13}$$

Substituting Eq. (13) into Eq. (9) yields Eq. (14).

$$0 = (1 - R_{combined}) \times (\dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t)) + \dot{m}_{cw,in}(t) \times C_{cw} \times T_{in}(t) - \dot{m}_{cw,eff}(t) \times C_{cw} \times T_{eff}(t) - \dot{m}_{cw,evap}(t) \times h_{vap}. \tag{14}$$

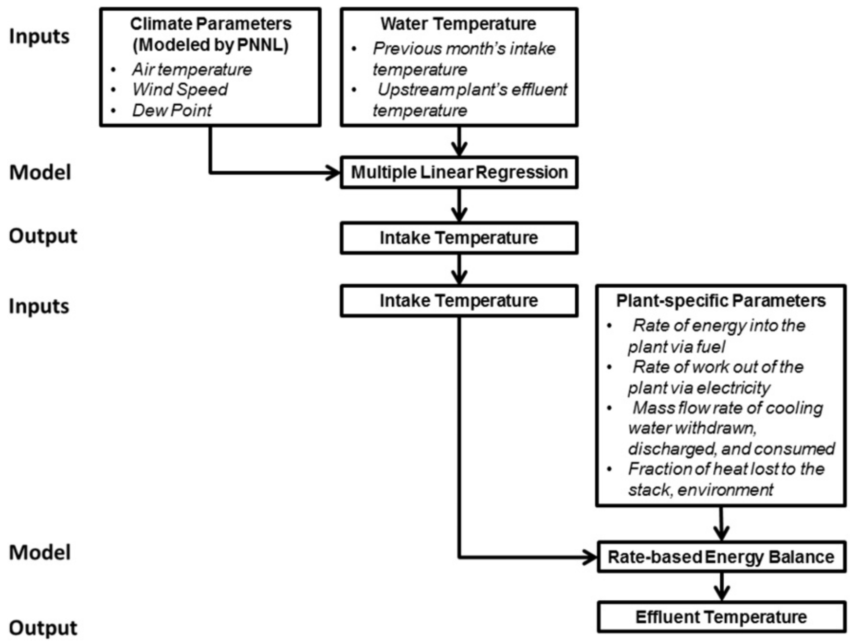

Fig. 4. Included in the flow chart are the combination of climate, regression, and thermodynamic models for calculating effluent temperature of certain power plants in the UMRB and GCB.

Isolating the effluent temperature in (14) gives Eq. (15).

$$T_{eff}(t) = ((1 - R_{combined})(\dot{E}_{chemical,in}(t) - \dot{E}_{electricity,out}(t)) + \dot{m}_{cw,in}(t) \times C_{cw} \times T_{in}(t) - \dot{m}_{cw,evap}(t) \times h_{vap}) \div (\dot{m}_{cw,eff}(t) \times C_{cw}). \quad (15)$$

A summary of this process, including the multiple linear regression in Eq. (1) and the energy balance in Eq. (15), is shown in Fig. 4. Historical water use, effluent temperature, energy generation, and fuel use data were extracted from the EIA form 923 (US EPA, 2012; US EIA, 2015). The waste heat, $R_{combined}$, was estimated from historical data. Data availability for monthly cooling limited calibration of Eq. (15) to the four year test period used throughout this analysis (2010–2013).

2.2.1. Limitations on the implementation of the energy balance

The model included in Eq. (15) should only be used on power plants with open-loop cooling or recirculating cooling involving a cooling pond as most or all of the water is returned back to the environment. Because of the much larger volume of water discharged from open-loop or recirculating cooling plants with cooling ponds compared to plants with cooling towers, which dissipate the vast majority of the heat by releasing it into the air via evaporated water (and thus largely do not discharge heat, or heated water, to aquatic environments), they are more likely to face issues with thermal discharge limitations which is the concern of this analysis. Moreover, recirculating plants with a cooling tower are thermodynamically different from open-loop cooling or recirculating cooling plants because of the additional energy required to operate the blowers in a cooling tower. The energy balance could be amended to include the additional energy requirement for a cooling tower with specific attention to the large volume of water evaporated from the tower. A power plant using dry cooling would also have a different approach to modeling cooling, but might be able to apply the energy balance using mass flow of air in and out of the plant rather than water.

To minimize error associated with changes in plant behavior, months in which the plant operated at less than half of the average hours per month compared to other months in the study period 2010–2013 were removed as outliers. Months in which the plant operated at low levels are not of interest as discharge temperature is not likely to exceed effluent temperature limits. Thus, if a plant is operating at lower than normal levels (for example if it is under maintenance), the energy balance model should not be used to estimate effluent temperature.

3. Results and discussion

3.1. Use of the intake temperature model and discussion of error

The reported and estimated average monthly intake temperatures are shown in Fig. 5. The average standard error for all plant models is 2.66 °C. While the specific numbers have disagreement, the general similarity in the patterns affirms that the model is generating results consistent with observation.

The results from the intake model could be used in planning at power plants concerned about exceeding their permitted intake temperature limit, about reduced cooling efficiency due to higher intake temperatures, or about reduced ability to cool water due to higher water temperatures and effluent temperature constraints. While these results are suitably accurate for multi-decade planning purposes, the level of error associated with this model makes it difficult to use in day-to-day operations requiring more precision. For those situations, real-time monitoring with instrumentation is more appropriate and is the typical approach.

There is uncertainty associated with each climatic estimate and reported intake and effluent temperatures; this uncertainty increases the uncertainty in the regression model itself. The estimates for $\beta_0 - \beta_5$, their tests for significance, and the standard error of the regression are included in Table 2. The standard error for each of the regression models ranges between 1.54 and 6.70 °C.

Using only 2010–2013 data has inherent uncertainty for predicting weather behavior of all subsequent years as it is not a complete representation of weather patterns. In addition, the intake temperatures used to calibrate the regression models carry their own reporting error; the EIA and EPA databases from which the intake temperatures were extracted are only as reliable as the reporting from power plant operators. The river flowrate, as well as snowpack and rainfall, affect the temperature of the river and the

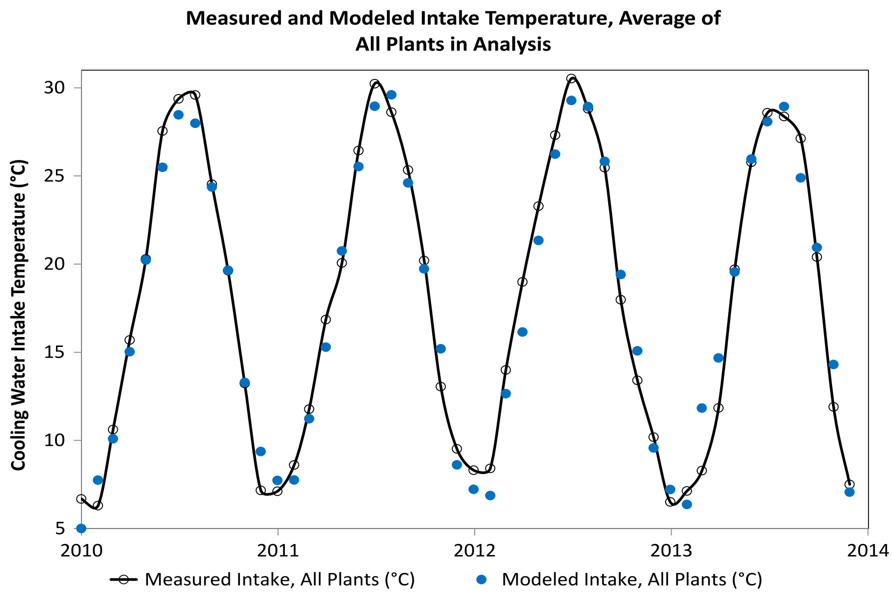

Fig. 5. The average historical reported monthly intake temperatures and the calculated intake temperature for all of the plants in the study are shown. *Source:* US EPA (2014) and US EIA (2015).

Table 2
The estimated values for the regression constants, β_0–β_5, are shown for the plants analyzed in this study. Negative values are shown in parenthesis. The plant ID numbers are those used by the EIA. The standard error is that of the regression analysis.

Plant ID	β_5	β_4	β_3	β_2	β_1	β_0	Standard error
204	0.52	(0.71)	0.11	0.21	0.00	9.75	2.20
856	0.42	0.40	0.41	0.07	0.15	1.89	4.84
874	0.30	(0.03)	0.31	0.40	0.00	6.93	1.92
876	0.54	0.36	0.23	0.29	0.00	3.90	2.32
880	0.44	0.82	0.22	0.28	0.19	(2.81)	2.05
884	0.41	0.12	(0.03)	0.27	0.19	3.72	1.66
889	0.42	1.25	0.43	0.27	0.00	4.49	2.14
892	0.37	0.67	0.10	0.20	0.50	(8.05)	1.81
898	0.42	0.84	0.20	0.25	0.25	(4.24)	2.00
1047	0.34	(1.31)	(0.14)	0.16	0.54	(0.83)	3.82
1081	0.52	0.05	0.27	0.25	0.00	4.52	2.23
1104	0.59	0.69	0.22	0.29	0.00	(0.12)	3.32
1167	0.39	(0.63)	0.38	0.28	0.00	9.10	2.78
2107	0.27	0.56	0.39	0.19	0.37	(4.44)	1.96
3457	0.50	(1.88)	0.16	(0.02)	0.00	18.83	2.19
3601	0.08	(2.19)	0.70	0.15	0.00	16.74	6.27
3611	0.47	(1.97)	0.01	0.19	0.00	17.35	1.57
4140	0.49	(2.08)	0.08	0.19	0.00	16.01	2.70
4271	0.55	(2.21)	(0.00)	0.19	0.00	15.51	2.78
4939	0.41	(1.50)	0.24	0.03	0.00	18.44	1.79
6136	0.34	(1.59)	0.40	0.03	0.00	15.94	1.54
6155	0.34	0.94	0.16	0.25	0.35	(6.71)	1.59
6181	0.47	(1.97)	0.01	0.19	0.00	17.35	1.57
6243	(0.13)	(3.62)	0.62	0.40	0.00	17.73	6.70
6251	0.40	(1.67)	0.09	0.16	0.00	17.26	1.71
7097	(0.23)	(4.17)	0.62	0.15	0.00	31.98	3.66

ability to dissipate heat from the upstream plant or another point source in the river. These and other potential impacts on the river, such as radiative adsorption, could lead to error in the model as they were not included.

Examples of the implementation of Eq. (1) are shown in Figs. 6 and 7. Of the twenty-six plants at which the intake temperature model was applied, the model shows that two plants could face increases in intake temperature between 2015 and 2035 compared to the 2010–2013 baseline. This is a conservative estimate compared to studies looking at surface water temperatures in the 21st century. Segura et al., estimated an increase of 0.41 °C per decade from 2010 to 2060 in 61 rivers modeled in the southern United States, compared to a 0.1 °C increase per decade from 1961 to 2010 (Segura et al., 2015). Stefan et al. modeled surface water temperature in lakes in Minnesota and found the water temperature near the surface is projected to increase by no more than 2 °C in midsummer (Stefan et al., 1993). Each of the plants with elevated intake temperatures (shown in Fig. 6) might face reductions in cooling efficiency as a direct result of these high intake temperatures.

3.2. Use of the rate-based energy balance and discussion of error

An example of the implementation of Eq. (15) is shown in Fig. 8.

Estimates generated using the combined energy balance and intake model are about 0.012 °C from the historical values with a standard deviation of 2.11 °C. Comparing absolute values of error, estimates differ from the reported values by an average 2.08 °C with a standard deviation of 1.45 °C over the four year period.

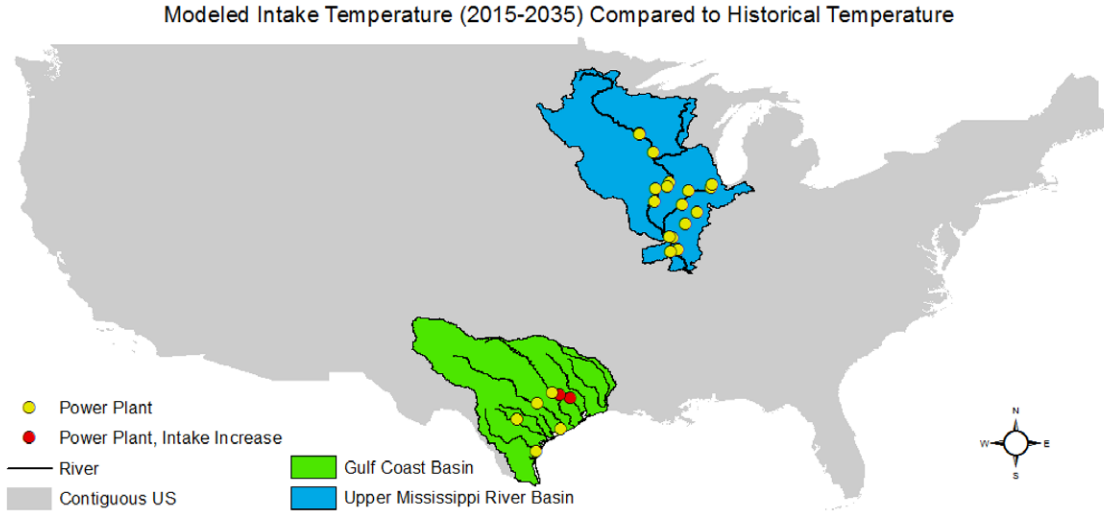

Fig. 6. Two of the plants modeled in this analysis, shown in red, could face elevated intake temperatures between 2015 and 2035 compared to the 2010–2013 baseline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

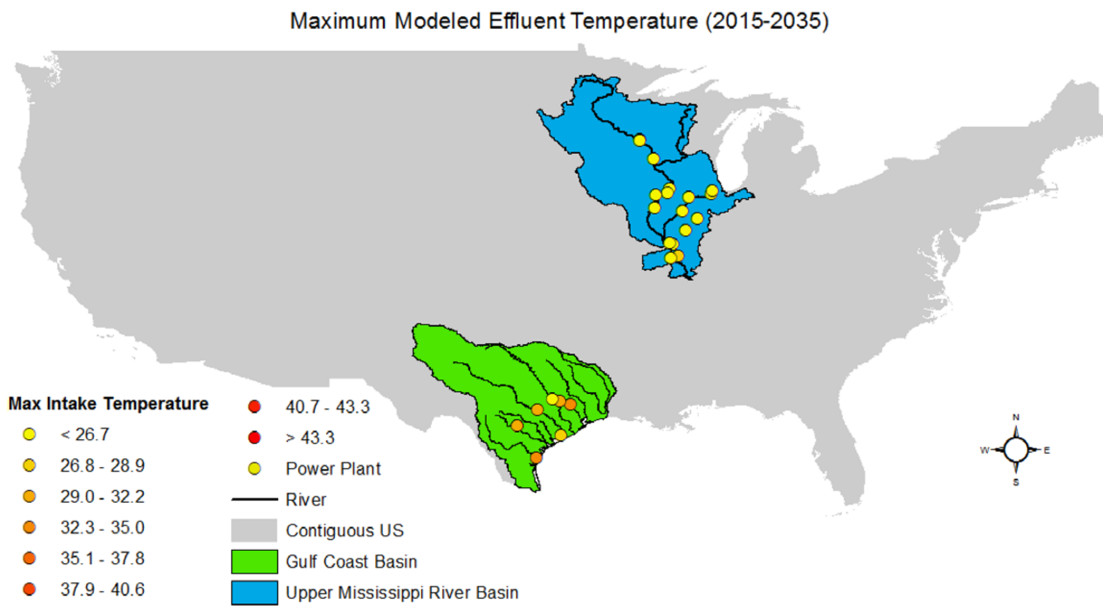

Fig. 7. Intake temperature is important for cooling efficiency and safety of equipment. Moreover, intake temperature approaching effluent temperature limits increase a power plant's risk of exceeding the limit and reduce cooling capability per unit of water. Six plants modeled in this analysis could face intake temperatures in excess of 28.9 °C between 2015 and 2035.

The data extracted from the EIA for this analysis are only reliable if reporting from power plant operators is reliable. Error in the model could also be attributed to variation in plant operations. The model estimates monthly performance, but a plant might change behavior daily.

Modeled effluent temperatures in the UMRB were compared to limits reported by Madden et al. (2013). The rise over ambient standard was applied to plants in Texas using the intake temperature as the ambient temperature. In this comparison, it is assumed that plants do not have variances, are subject to state summer effluent temperature limits, and no mixing zone is applied. In estimating future temperatures, it is assumed that plants will operate at similar levels between 2015 and 2035 as they operated at between 2010 and 2013. If plants increase electricity generation, withdrawals and effluent temperatures could increase, making plants more vulnerable to water stress. Table 3 shows the results of comparing modeled future effluent temperatures to current state regulations, including the number of summer months (June, July, and August) from 2015 to 2035 in which the plant would exceed the state regulation. The power plants are also shown in Fig. 9.

While generating at 2010–2013 levels, eleven of the plants in the UMRB and GCB study areas could discharge average monthly intake temperatures in excess of 29.8 °C between 2015 and 2035. Nine of the plants could discharge average monthly intake temperatures in excess of 32.2 °C. One of the plants could discharge at monthly effluent temperatures in excess of 43.3 °C. The plants are shown in Fig. 10. If the plant is not subject to a permitted effluent temperature limit, heated effluent could still impact the environment into which cooling water is discharged, including increasing the evaporation in a potentially water-stressed area.

It is important to note that climate change might cause increased surface water temperatures throughout the year, however the effects of elevated temperatures from climate change or heat waves might cause issues at power plants only at certain times of the year when electricity demand peaks. If water temperatures increase at times when electricity demand is not at its peak, other plants in the network not facing elevated

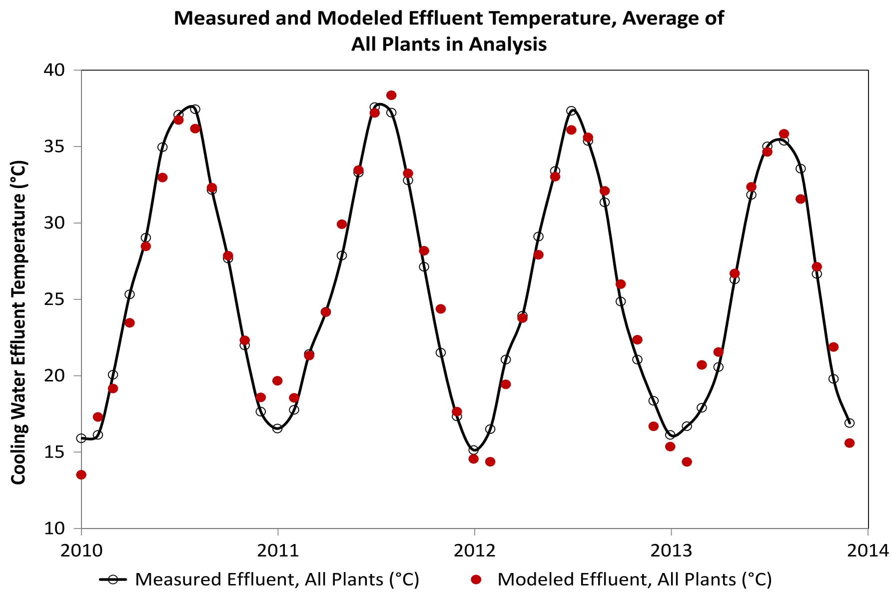

Fig. 8. The average historical average monthly effluent temperature and the estimated effluent temperature is shown for all power plants analyzed. *Source:* US EPA (2014) and US EIA (2015).

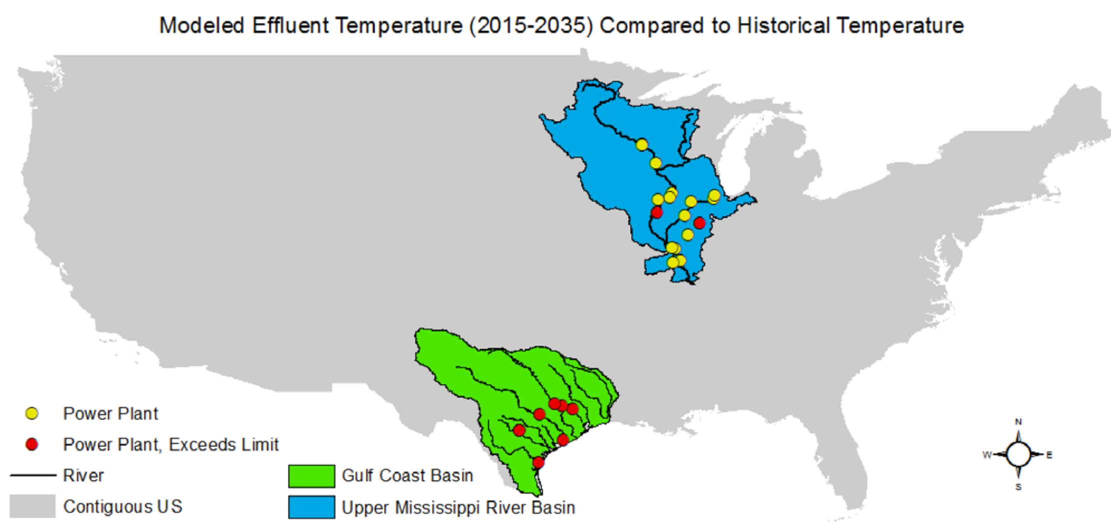

Fig. 9. The modeled effluent temperatures were compared to limits reported by Madden et al. (2013). The results showed eleven plants would exceed the statewide limits.

Table 3
The modeled effluent temperatures were compared to limits reported by Madden et al. (2013). The results showed eleven plants would exceed the statewide limits.

Plant ID	Number of summer months model shows plant exceeds limit	State
204	39	IL
1104	46	IA
3457	63	TX
3601	21	TX
3611	63	TX
4939	63	TX
6136	63	TX
6181	63	TX
6243	63	TX
6251	63	TX
7097	63	TX

temperatures or limitations on discharge temperature that would previously not have operated might be able to generate electricity in place of plants with discharge issues. This substitution could come at a higher cost of generation but would not necessarily cause black-outs or brown-outs due to lack of supply. If power plants have challenges with cooling during peak times, the plant would have to choose between exceeding the discharge limit and generating electricity to meet demand or curtailing electricity at the potential detriment to the electricity system. The method outlined in this paper is meant to highlight that constraints could arise and more integrated water and energy planning could help offset any future problems before they occur.

4. Conclusions

Ongoing drought has revealed the vulnerability of thermoelectric power plants to the risks of low water levels coupled with high water temperatures. In this analysis, a linear regression model of environmental factors is used to estimate the intake temperature of water for cooling a power plant. These factors include dry bulb air temperature, dew point, intake temperature, wind speed, and effluent temperature of the upstream plant. Subsequently, the intake temperature information is used with a rate-based energy

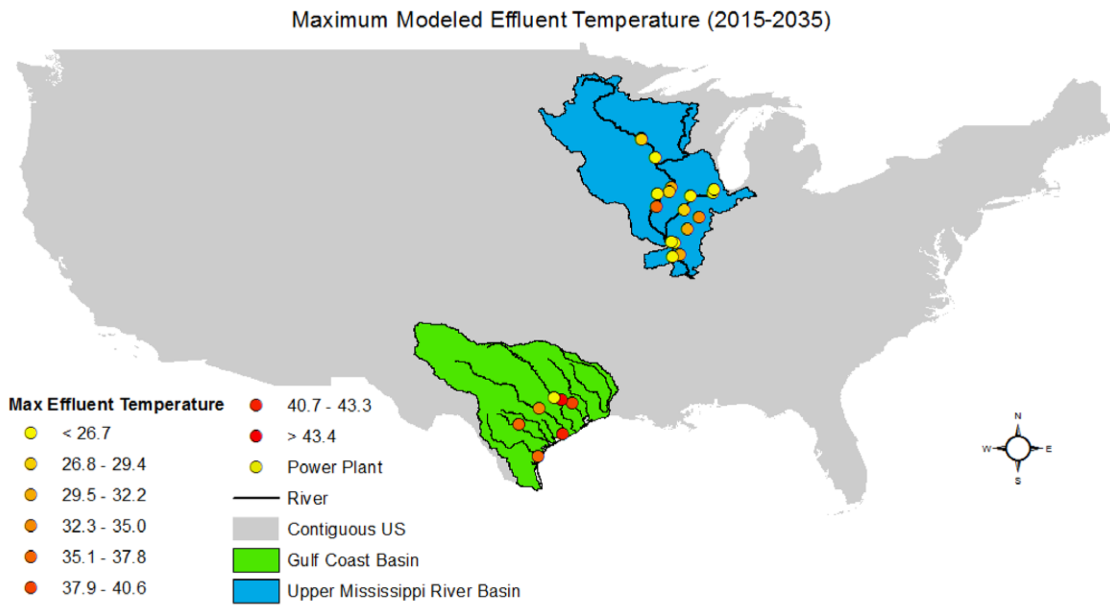

Fig. 10. Rising intake temperatures could result in rising effluent temperatures at power plants. Eleven plants in the UMRB and GCB could discharge water above 29.8 °C. Nine plants could discharge water above 32.2 °C. One plant could discharge effluent in excess of 43.3 °C.

balance on the mechanical system to estimate the effluent temperatures. For the years modeled, 2010–2013, the combined regression and energy balance estimates effluent temperature that is on average within 0.01 °C of the observed values, with a standard deviation of 2.11 °C. The models were then used to estimate intake and effluent temperatures for the period 2015–2035. Results show two plants could face elevated intake temperatures and three plants could discharge higher effluent temperatures between 2015 and 2035 compared to the 2010–2013 baseline. Eleven plants could discharge at monthly temperatures in excess of 29.8 °C. One plant could discharge at monthly effluent temperatures in excess of 43.3 °C. Twelve plants could discharge temperatures in excess of the statewide summer limits on effluent temperature.

There are many ways power plants mitigate issues with low water levels and high temperatures. Designing plants for potentially scarce water resources and making policies that protect water supplies and support energy resources might become more relevant in the future.

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Appendix A. Background information

A.1. Effluent temperature regulations

Heat is a unique type of pollutant. It does not accumulate in the environment, nor is it a toxic or hazardous substance, although excessive heat can harm native aquatic organisms when temperatures exceed naturally-occurring conditions (Veil, 1993). Upon entering a body of water, heat rapidly dissipates to the surrounding water and to the atmosphere, so its impacts are limited to a relatively local zone around the source of heat. Heat is not included in the EPA's list of priority pollutants (US EPA, 2013). However, by implementing effluent temperature limits set by the National Pollutant Discharge Elimination System (NPDES) program, the EPA regulates heated discharges from power plants that withdraw and release water back into the environment (Veil, 1993).

In addition to the federal regulations, states also regulate effluent temperature. For example, the Texas Administrative Code (TAC ∮∮ 307.4) includes specific regulations for effluent temperature from power plants. In freshwater streams, the temperature differential between discharge and the environment cannot exceed 2.8 °C; in freshwater lakes and impoundments, the temperature change cannot exceed 1.7 °C; and in tidal river reaches, bay, and gulf waters, the temperature differential cannot exceed 2.2 °C in the fall, winter, and spring, or 0.8 °C in June, July, or August (Texas, 2014). Plants in Texas might also have specific permits limiting their thermal discharge to an absolute limit. Other states might have policies regarding absolute maximum discharge temperature rather than a differential. Madden et al. found that across the United States, at least 14 of the 15 states with the most once-through cooling systems have set standards to ensure that freshwater temperatures do not exceed 32.2 °C (Madden et al., 2013; King, 2014). The study reported absolute effluent limits for many states used in this analysis (shown in Table A.4). In Iowa, Missouri, and Wisconsin, the discharge temperature is allowed to exceed the limit by 1.7–2.8 °C. This allowed exceedance over the absolute limit is also included in Table A.4.

A.2. Response to high temperatures

Power plants across the United States have encountered water and temperature constraints that led to decreased operability. Drought in the Southeastern states during 2007 and 2008 posed a risk to baseload thermoelectric generation facilities (Wagman, 2013). Perpetual drought and increased temperatures in Texas caused certain thermoelectric facilities to reduce electricity

Table A.4
Maximum summer temperatures for surface waters, as reported by Madden et al. are shown for four states in the UMRB (Madden et al., 2013). In Iowa, Missouri, and Wisconsin, discharge temperature is allowed to exceed the limit. This allowed exceedance is shown in parenthesis next to the absolute limit. The statewide limit for lakes and impoundments in Texas as listed in TAC ∮ ∮ 307.4 is also shown in the table.

State	Summer temperature limit for surface waters
Illinois	32 °C
Iowa	30 (+1.7 °C)
Missouri	32.2 (+1.8 °C)
Texas	1.7 °C rise over ambient
Wisconsin	28.9 (+2.8 °C)

generation in 2012 while extraordinarily low temperatures shut down power plants in the state and in the Southwest in February 2011 (Galbraith, 2011; National Public Radio, 2012; Federal Energy Regulatory Commission, 2011). There are many other instances of these curtailments around the world (Associated Press, 2012; Souder et al., 2011; Forster and Lilliestam, 2010; Illinois Environmental Protection Agency, 0000; Robine et al., 2008; Hightower and Pierce, 2008; Poumadere et al., 2005; Lagadec, 2004; Godoy, 2006).

In the summer in Texas, higher electricity demand is correlated with increases in air temperature (because of demand for air conditioning). The resulting increase in power generation to meet the demand requires that a larger supply of heat is transferred to the cooling water at the same time that cooling efficiency is reduced (Karl et al., 2009). In other parts of the world, peak demand is at night for electric heating in winter months. However, when water levels are low, plants might not have the option to withdraw at a higher rate, in which case the power plant is de-rated and its output is turned down. Similarly, if the plant's discharge temperature is subject to maximum daily, average daily, and average monthly temperature limits, the plant might not be allowed to heat the withdrawn water to higher temperatures without exceeding those discharge limits, which also causes de-rating of the power plant. Moreover, with higher cooling water temperatures at the intake of the plant (either because of the hotter meteorological conditions, or because of thermal loading from other users upstream), less additional heat can be transferred from the power plant to the environment than could be transferred under cooler ambient conditions. Because of this thermal constraint, at times of high electricity demand more water is needed for cooling, but the same conditions that drive higher water temperatures also occur at times when water levels are low. That is, higher temperatures trigger demand for more power generation that occurs at times when less water can be used to operate those same power plants. When water levels are low, there is less water to store the same quantity of heat. Consequently, in the midst of a heat wave, a power plant might face a decreased ability to shed as much heat with the same amount of cooling water while simultaneously having to meet higher demand. In this situation, the power plant might be forced to curtail its electricity generation despite the increased demand for that electricity. In summary, cooling water that is warmer and scarcer than normal can reduce the power plant's efficiency and/or limit its net power generation. The efficiency is reduced because of (1) reduced heat transfer in the cooling system or (2) increased parasitic load from higher cooling water pumping rates. The net power generation can be reduced if the power plant is at risk of violating its thermal water discharge limits in its environmental permit. This risk to loss of generation is important because: (1) it affects the reliability of the power system and puts human lives at risk, and (2) decisions are made today about long-lived capital assets that might be operating under different climatic conditions in the future. Therefore, analysis and methods as presented in this paper can be used to inform those decisions with the intent of improving the reliability of current and future power sector.

Table B.5
Included in this table are the estimated values for, $R_{combined}$. The ratios included here refer to once-through or recirculating cooling systems with cooling ponds.

Plant ID	$R_{combined}$
204	0.22
856	0.12
874	0.35
876	0.42
880	0.02
884	0.24
889	0.11
892	0.24
898	0.12
1047	0.27
1081	0.20
1104	0.22
1167	0.06
2107	0.19
3457	0.24
3601	0.22
3611	0.04
4140	0.35
4271	0.46
4939	0.48
6136	0.14
6155	0.08
6181	0.21
6243	0.45
6251	0.42
7097	0.08

Appendix B. Supporting tables

(See Table B.5.)

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Glossary

NPDES: National Pollutant Discharge Elimination System.
UMRB: Upper Mississippi River Basin.
GCB: Gulf Coast Basin.
EPA: Environmental Protection Agency.
$T_{eff}(t)$: Effluent temperature in month t.
$T_{DB}(t)$: Dry bulb air temperature in month t.
$T_{DP}(t)$: Dew point in month t.
$T_{in}(t)$: Inlet water temperature in month t.
$T_{in}(t-1)$: Inlet water temperature in month $t-1$.
$V(t)$: Wind speed in month t.
$T_{up}(t)$: Effluent temperature of the upstream plant in month t.
β_0: Regression constant.
β_1: Regression coefficient for $T_{up}(t)$.
β_2: Regression coefficient for $T_{in}(t-1)$.
β_3: Regression coefficient for $T_{DP}(t)$.
β_4: Regression coefficient for $V(t)$.
β_5: Regression coefficient for $T_{DB}(t)$.
EIA: Energy Information Administration.
R^2: Coefficient of determination.
MSE: Mean square error.
n: Number of observations used for the regression analysis.
α: Significance level.
$\dot{E}_{final}$: Final rate of energy transport.
$\dot{E}_{initial}$: Initial rate of energy transport.
$\dot{E}_{in}$: Energy flows into the system.
$\dot{E}_{out}$: Energy flows out of the system.
$\dot{E}_{chemical,in}$: Rate of energy input via fuel.
$\dot{E}_{electricity,out}(t)$: Rate of work output via electricity.
$\dot{E}_{air,in}$: Rate of energy input in air.
$\dot{E}_{cw,in}$: Rate of energy input in cooling water.
$\dot{E}_{stack,out}$: Rate of energy output via stack gases.
$\dot{E}_{cw,out}$: Rate of energy output via cooling water.
$\dot{E}_{cw,evap}$: Rate of energy output via evaporated cooling water.
$\dot{m}_{CW,final}(t)$: Final mass flow rate of the cooling water.
$\dot{m}_{CW,initial}(t)$: Initial mass flow rate of the cooling water.
$\dot{m}_{CW,in}(t)$: Mass flow rate of the cooling water into the plant.
$\dot{m}_{CW,out}(t)$: Mass flow rate of the cooling water out of the plant.
$\dot{m}_{CW,eff}(t)$: Mass flow rate of the effluent cooling water.
$\dot{m}_{CW,evap}(t)$: Mass flow rate of the evaporated cooling water.
C_{cw}: Specific heat of water.
$h_{vap}(t)$: Enthalpy of vaporization of water.
$\Delta T(t)$: Difference between intake and effluent temperature.
$R_{air,in}$: Ratio of the rate of energy into the plant via air to the rate of total energy out of the plant.
$R_{stack,out}$: Ratio of the rate of energy out via stack gases to the rate of total energy out of the plant.
$R_{other,out}$: Ratio of the rate of other energy out to the rate of total energy out of the plant.
$R_{combined}$: Combined ratio of the rate of energy flows out of the plant to the rate of total energy out.