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Horizontal cooling towers: riverine ecosystem services and the fate of thermoelectric heat in the contemporary Northeast US

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Abstract
The electricity sector is dependent on rivers to provide ecosystem services that help regulate excess heat, either through provision of water for evaporative cooling or by conveying, diluting and attenuating waste heat inputs. Reliance on these ecosystem services alters flow and temperature regimes, which impact fish habitat and other aquatic ecosystem services. We demonstrate the contemporary (2000–2010) dependence of the electricity sector on riverine ecosystem services and associated aquatic impacts in the Northeast US, a region with a high density of thermoelectric power plants. We quantify these dynamics using a spatially distributed hydrology and water temperature model (the framework for aquatic modeling in the Earth system), coupled with the thermoelectric power and thermal pollution model. We find that 28.4% of thermoelectric heat production is transferred to rivers, whereas 25.9% is directed to vertical cooling towers. Regionally, only 11.3% of heat transferred to rivers is dissipated to the atmosphere and the rest is delivered to coasts, in part due to the distribution of power plants within the river system. Impacts to the flow regime are minimal, while impacts to the thermal regime include increased river lengths of unsuitable habitats for fish with maximum thermal tolerances of 24.0, 29.0, and 34.0 °C in segments downstream of plants by 0.6%, 9.8%, and 53.9%, respectively. Our analysis highlights the interactions among electricity production, cooling technologies, aquatic impacts, and ecosystem services, and can be used to assess the full costs and tradeoffs of electricity production at regional scales.

Keywords: thermoelectricity, thermal pollution, water temperature, river ecosystem services, Northeast USA

S Online supplementary data available from stacks.iop.org/ERL/8/025010/mmedia

1. Introduction

Thermoelectric power plants are the largest users of freshwater in the United States (US) (Averyt *et al* 2011) and globally (Vassolo and Doll 2005). They provide 90% of electricity consumed in the US, and an even a greater proportion in the northeastern part of the country (Averyt *et al* 2011). Thermoelectricity production relies on biophysical processes of freshwater ecosystems to provide coolant or for conveyance, dilution, and attenuation of waste heat loads. As a result, power generation has the potential to stress freshwater ecosystems through both reduced river flows via consumptive use by cooling towers (Sovacool 2009, MacKnick 2011) and the discharge of thermal pollution. It is important to quantify anthropogenic water use and its implications (Postel and Richter 2003, King *et al* 2005) as overuse can result in significant degradation to river flow regime, biogeochemistry (Meybeck and Helmer 1989, Meybeck 2003) and aquatic habitat (MEA 2005). Here we apply the ecosystems services concept (Smakhtin *et al* 2004, Sweeney *et al* 2004, Richter *et al* 2006, Brauman *et al* 2007) to understand how aquatic ecosystems support a critical economic activity, thermoelectric power production.

The two most commonly applied methods for thermoelectric plant cooling are 're-circulating cooling' or RCC, which typically utilize evaporative cooling towers; and 'once-through cooling' or OTC, where waste heat is transferred directly to rivers (Averyt *et al* 2011). Both approaches rely on aquatic ecosystem services, with the former requiring consumptive water use, and the latter depending on transport, dilution, and dissipation processes in natural waterways (Brauman *et al* 2007). Electricity production at both OTC and RCC plants are inherently linked to ambient air and water temperatures, as output efficiencies decrease with elevated intake temperatures (NETL 2002, Miara and Vorosmarty 2013). Thermoelectric plants that do not withdraw or consume water from river systems include those that implement alternative methods (i.e. dry cooling) and those that use marine sources, and represent 4.1% and 10.6% of the total number of thermoelectric plants within the region, respectively. In the face of changing climate and increasing energy demand (Wilbanks *et al* 2008), it is essential to assess the capacity and associated environmental tradeoffs (Bennett *et al* 2009) of heat regulating ecosystem services that support the electricity sector.

If river systems were nothing more than networks of nonconductive pipes, 100% of heat loads from power plants would be delivered to receiving oceans and stream temperatures would reflect the conservative mixing (i.e. dilution) of heat inputs. However, rivers are interactive pathways that continuously exchange energy with the atmosphere (Edinger *et al* 1968, Dingman 1972, Webb and Nobilis 1997, Webb *et al* 2003, Wilhelm *et al* 2006, Pedersen and Sand-Jensen 2007, Austin and Allen 2011). The river's ability to mitigate thermal pollution is a function of river length, channel dimensions, discharge magnitude and velocity, and atmospheric conditions (i.e. wind speed, difference between water and air temperature, relative humidity, and solar radiation) (Edinger *et al* 1968, Dingman 1972). Entire river networks thus have the potential to buffer significant amounts of upstream anthropogenic heat loading and reduce downstream thermal pollution. Recently developed models have predicted water temperatures in a changing climate (van Beek *et al* 2012, van Vliet *et al* 2012, Wu *et al* 2012), but have not quantified the capacity of river systems to attenuate anthropogenic heat loads.

Both OTC and RCC cooling methods come at potentially significant environmental costs, specifically, reduced river flow and increased water temperatures (Vassolo and Doll 2005, Averyt *et al* 2011). Re-circulating cooling towers withdraw relatively small volumes from the river, but these withdrawals are mostly consumptive, thereby putting fish habitat and other downstream water uses at risk during low flow periods. Once-through cooling technologies are less consumptive of water but require substantial water withdrawals and return flows are at elevated temperatures. Increased water temperatures can reduce the abundance and connectivity of suitable habitats for native fish and can create refugia for cold-intolerant invasive species (Morgan *et al* 2003, Rosa *et al* 2012).

Here we apply a spatially distributed river water temperature model coupled with a thermoelectric power plant model (TP2M) to characterize the contemporary (2000–2010) dependence of electricity production on freshwater ecosystem services, and the resulting impact on receiving freshwaters. We apply this model to rivers in the Northeast US, which contains a high density of thermoelectric power plants serving the region's high energy demands (Wilbanks *et al* 2008). Specifically, our goals are to (1) calculate how much regional electricity production depends on engineered cooling towers versus riverine 'horizontal cooling towers' for transferring heat away from thermoelectric power plants, (2) quantify the benefit that thermoelectric power plants receive from the regulation of excess heat by freshwaters, and (3) assess the consequences of relying on these riverine ecosystem services in terms of altered freshwater temperatures and flow regimes.

2. Quantifying the heat regulating ecosystem services of rivers

To assess thermal regulating ecosystem services provided by river systems, we require spatially distributed models that integrate the distribution, type and size of power plants, their water demands and heat loads, and hydrologic and thermal conditions throughout the river system. Models must account for natural and anthropogenic heat loading, discharge, and re-equilibration by aquatic systems. We embedded power plant and water temperature models in the framework for aquatic modeling in the Earth system (FrAMES) (Wollheim *et al* 2008a, 2008b, Wisser *et al* 2010, Stewart *et al* 2011) to simulate river flows, electricity generation, and water temperatures in the Northeast US at a spatial resolution of 3 min (latitude/longitude) (figure S.1, available at stacks.iop.org/ERL/8/025010/mmedia). FrAMES utilizes the water balance model (WBM) and water transport model (WTM) (Vorosmarty *et al* 1998, Wisser *et al* 2010) for the coupled simulation of the vertical water exchange between the land surface and the atmosphere and the Muskingum–Cunge routing of horizontal water transport (Ponce 1994) through branching river segments. This spatially distributed, gridded river network model was updated with modules to account for transport, mixing and re-equilibration of water temperatures along river reaches at a daily time step. Model results match well with United States Geological Survey (USGS) observations for discharge ($n = 694$ stations) and water temperature ($n = 243$ stations) in basins ranging from 200 to 70 200 km^2 (figures S.2, S.3, available at stacks.iop.org/ERL/8/025010/mmedia). Model input data includes total daily precipitation, average daily air temperature, cloud cover, and wind speed which were acquired from NASA's Global Modeling and Assimilation Office (Modern Era-Retrospective analysis for Research and Applications or MERRA). Model output was summarized for quantification of summer (June, July, August), winter (December, January, February), and annual impacts. Tidal influences were not incorporated in the current version of the model; thus, reported values for thermal impacts are in terms of exported freshwater temperatures only. A detailed summary of each model, their linkages, input data, and validation is described in the supplementary material (available at stacks.iop.org/ERL/8/025010/mmedia).

The non-point thermal loading model (NTLM) was used to generate runoff heat fluxes as the product of (1) surface and groundwater runoff inputs to each individual river grid cell and (2) their associated temperatures. Precipitation was assigned the mean daily air temperature in each grid cell, whereas snowmelt was assigned a temperature of 0 °C. Surface runoff temperatures are volume-weighted mixtures of precipitation and snowmelt temperatures, whereas groundwater runoff temperatures are the result of volume-weighted mixtures of percolation temperatures that comprise shallow ground water. Similar models have been developed for other domains, including global (van Beek *et al* 2012, van Vliet *et al* 2012) and regional northwestern US (Wu *et al* 2012). Runoff and its water temperature from the local grid cell are then mixed with routed fluxes from upstream and any storage existing in the river channel from the previous time step.

Re-equilibration of water temperatures during flow routing through the river network is computed using the river temperature re-equilibration model (RTRM). This method is based on a combined empirical and deterministic approach outlined in Dingman (1972). The method is appropriate for large scale applications (Mohseni and Stefan 1999, Bogan *et al* 2003, Pedersen and Sand-Jensen 2007, Austin and Allen 2011), including lakes and large rivers (Morse 1972) and is based on the theory of equilibrium temperature—the temperature at which there is no net exchange of energy with the atmosphere (Edinger *et al* 1968, Dingman 1972, Webb *et al* 2003).

The thermoelectric power and thermal pollution model, or TP2M (Miara and Vorosmarty 2013), was applied to simulate power plant operations including withdrawals, consumption (evaporation), and resulting return flows and temperatures to the river network corresponding to electricity demand. TP2M accounts for reduced power plant efficiency and electricity generation when cooling water temperatures in the power plant condenser increase above a threshold temperature. Historical reported values (2000–2010) for monthly power generation at all 384 thermoelectric power plants along rivers in the region (figure 1) were used to simulate the daily heat loads at each location. WBM, WTM, NTLM, RTRM, and TP2M are fully coupled with one another in FrAMES (figure S.1) and dynamically simulate the spatially distributed waste heat loads to the river system accounting for various cooling technologies (OTC, RCC, dry cooling, and hybrid combinations), and fuel types. Thermoelectric power plants that withdraw cooling water from the Atlantic Ocean were not included in this study. Input data requirements for TP2M were assembled from a variety of sources including the US Energy Information Administration (EIA) and Union of Concerned Scientist (UCS) databases and application of standard thermodynamic equations.

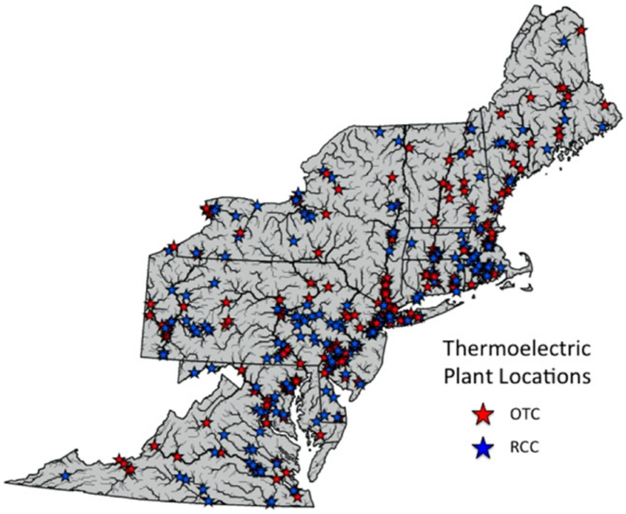

Figure 1. Locations of freshwater once-through cooling (OTC, red) and re-circulating cooling (RCC, blue) thermoelectric power plants within the study domain. Dry cooling and other hybrid technologies ($n = 19$ plants) and those that withdraw from marine sources and the Great Lakes ($n = 47$ plants) are not shown. Contributing hydrological drainage areas that fall outside of political boundaries were simulated but not displayed.

3. Riverine ecosystem services and the fate of thermoelectric heat

Of the total heat generated by thermoelectric power plants in the Northeast US between 2000 and 2010, 34.3% was converted to electricity, 28.4% was transferred directly to rivers (OTC plants), 25.9% was dissipated via consumptive water use in engineered cooling towers (RCC plants), and the remainder was lost during the cooling process to sinks (Rutberg *et al* 2011) other than the condenser (figure 2). The electricity sector in this region therefore relies as heavily on rivers as it does on engineered evaporative cooling towers to convey heat from plants during electricity generation. Thermoelectric power plants within the region draining to the Atlantic produced a total of 461.0 TWh yr^{-1} of electricity, 54.3% of which was generated by OTC plants (table 1). The ability of river systems to serve as horizontal cooling towers involves two supporting ecosystem services: downstream transport/dilution and heat dissipation in the

Table 1. Average annual thermoelectricity produced (2000–2010), the associated waste heat inputs to the river network, the resulting temperature increases at the river mouth due to thermal pollution, and the per cent of heat dissipated by the riverine ecosystem service.

	Thermoelectricity produced (TWh yr^{-1})			Heat input to river (PJ yr^{-1})			Heat concentration (TJ km^{-3} yr^{-1})	Freshwater temperature increase at river mouth (°C)			Heat attenuated by riverine ecosystem (%)		
Basin	OTC	RCC	Total	OTC	RCC	Net	Net	Sum.	Win.	Ann.	Sum.	Win.	Ann.
Atlantic	250.4	210.6	461.0	1055	−0.6	1054	4.5	1.9	0.9	0.9	11.9	12.9	11.3
Penobscot	1.7	2.9	4.6	7.6	0.0	7.6	0.5	0.2	0.1	0.1	7.6	22.3	10.5
Merrimack	13.3	2.5	15.8	25.5	0.0	25.5	3.1	1.0	0.6	0.6	19.1	33.6	22.2
Connecticut	23.4	2.7	26.1	50.3	0.0	50.3	2.6	0.8	0.4	0.5	20.3	39.6	23.8
Hudson	36.1	15.1	51.2	252.3	0.0	252.3	11.3	5.0	2.4	2.5	6.4	7.5	6.2
Delaware	12.2	58.6	70.8	86.7	−0.1	86.6	5.5	2.7	0.9	1.1	12.9	11.9	12.5
Susquehanna	33.8	36.4	70.2	239.7	−0.3	239.4	7.1	2.9	1.3	1.5	11.1	11.6	9.7
James	24.5	4.8	29.3	177.6	0.0	177.6	19.7	8.2	3.1	3.9	21.5	13.9	18.1

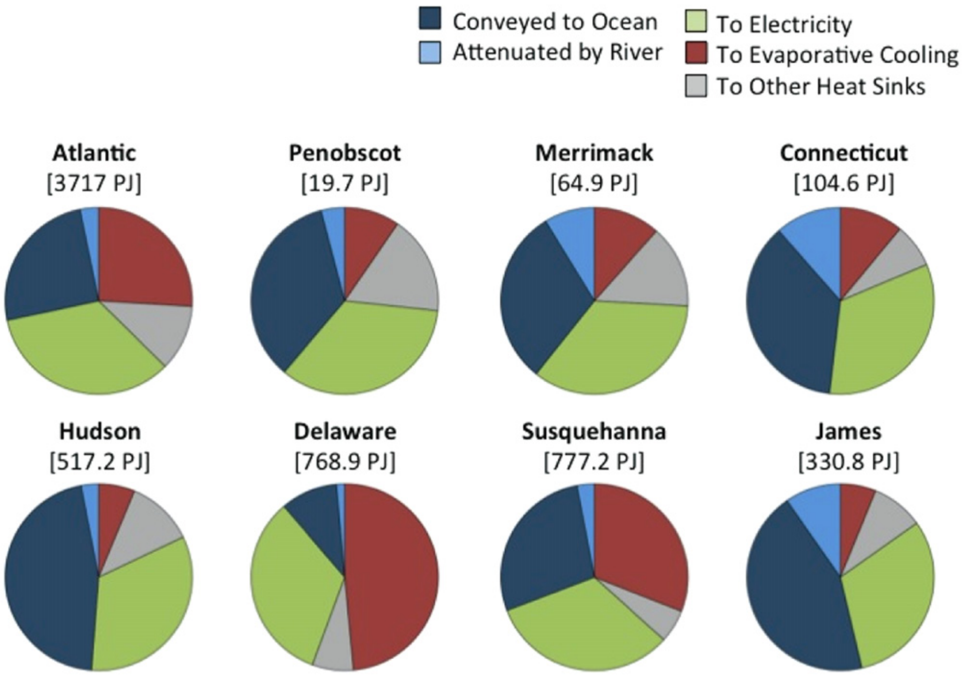

Figure 2. Allocation of total heat (in petajoules) generated in freshwater thermoelectric power plants during electricity production at selected basins, including heat to evaporative cooling towers (red), heat to electricity generation (green), heat lost to sinks other than the condenser (gray), heat to river (dark and light blue), heat attenuated by riverine ecosystem services (light blue), and heat conveyed to the ocean (dark blue).

rivers themselves. Our model suggests that, of the heat transferred to rivers draining into the Atlantic, 11.3% is dissipated, and the remainder (935.2 PJ yr^{-1}) is transported to oceans.

The regulating capacities of river networks vary by watershed, depending on the magnitude of heat inputs (table 1), the spatial distribution of power plants within the basin, and to a lesser extent climate conditions. Long flow paths from heat source to the river mouth provide greater opportunity for impacted water temperatures to reach equilibrium. Temperature regulation also varies slightly with season (12.9% of total river heat inputs removed during the winter, 11.9% during the summer). Average annual network scale heat removal in northeast basins range from 6.2% in the Hudson (6.4% in summer, 7.5% in winter) to 23.8% in the Connecticut (20.3% in summer, 39.6% in winter). Predicted increases in average freshwater temperatures exported at river mouths due to power plants range from 3.9° in the James (8.2° in summer, 3.1 in winter) to 0.1° in the Penobscot (0.2° in summer, 0.1° in winter). Actual water temperatures in the James are likely to be less elevated than simulated due to tidal dilution, which is not represented in our model. Tidal dilution impacts approximately the last 233 km and 170 km of the Hudson River and James River main stems, respectively.

Downstream thermoelectric power plants benefit from the service of heat dissipation by the upstream river network. To assess the benefits of this service, we calculated the average number of days per year in which water temperatures are below the critical OTC power plant operational threshold of 22 °C (EEA 2008, van Vliet *et al* 2011, Miara and Vorosmarty 2013) due to riverine heat dissipation. We made this calculation using model scenarios where power plant heat re-equilibration was and was not allowed to occur. Nearly half (48.6%) of freshwater OTC plants experienced some increase in the average number of days where intake river temperatures were optimal because of heat dissipation (figure 4), with the average benefit small (2.1 days) over the 11 year period. However, average benefits ranged from 0.1 to 22.7 days across individual plants depending on the upstream distance and magnitude of heat loads. Further, benefits increased during dry years, as three plants in the region gained over 41 optimal days during 2001, which suggests the thermoelectricity sector may rely more heavily on riverine ecosystem services under certain climate conditions, with implications for future climate changes.

In aggregate, OTC plants produce all of the total net annual heat loads to rivers (table 1) and many of the largest of these are located near basin mouths due to the large water withdrawals they require (Kenny *et al* 2009). As a result of this common spatial configuration, a significant amount of thermal pollution (1) escapes the river network, and (2) impacts other downstream plants near the basin mouth, with little heat reduction provided by the river's ecosystem service. In this sense, the ecosystem service provided by the regional network of rivers is generally limited to waste heat conveyance rather than attenuation. Exceptions include the Connecticut and Merrimack, where over one-fifth of annual waste heat inputs to each basin are dissipated (table 1).

Total annual heat inputs to rivers, standardized by total annual basin discharge, reveals a broad range in the concentration (defined as total heat/basin runoff) of annual heat loads (PJ km^{-3} yr^{-1}) and the dilution capacities among

Table 2. Count of thermoelectric power plants in each basin, the average distance for each type of plant to the river mouth (weighted based on total energy output), and the percentage of average summer flows (2000–2010) that are withdrawn and consumed during electricity production.

	Thermoelectric power plant count			Weighted distance (km)		Avg. summer withdrawals (%)			Avg. summer consumption (%)		
Basin	OTC	RCC	Ratio	OTC	RCC	OTC	RCC	Total	OTC	RCC	Total
Atlantic	185	169	1.1	123.4	238.8	22.1	0.5	22.6	0.1	0.4	0.5
Penobscot	6	2	3.0	49.6	65.6	1.1	0.0	1.1	0.0	0.0	0.0
Merrimack	6	4	1.5	104.5	93.1	10.4	0.1	10.5	0.1	0.0	0.1
Connecticut	16	8	2.0	134.9	94.0	30.0	0.0	30.0	0.2	0.0	0.2
Hudson	20	7	2.9	55.8	134.9	49.3	0.1	49.4	0.3	0.1	0.4
Delaware	20	25	0.8	60.4	103.4	25.9	2.4	28.3	0.2	1.9	2.1
Susquehanna	16	10	1.6	122.3	216.7	30.2	0.9	31.1	0.2	0.7	0.9
James	8	8	1.0	120.9	211.8	94.8	0.3	95.1	0.4	0.3	0.6

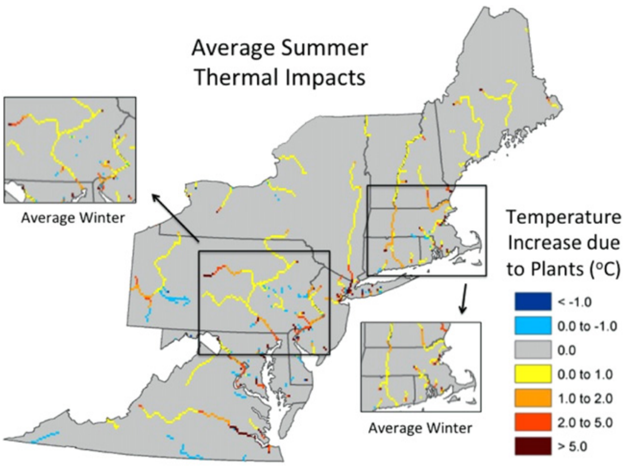

Figure 3. Increase in average summer water temperatures (2000–2010) due to thermal pollution from power plants. Callout boxes show results for average winter conditions in selected regions. Temperature increases due to plants are more widespread in the summer because waste heat inputs are dissipated more quickly in the winter.

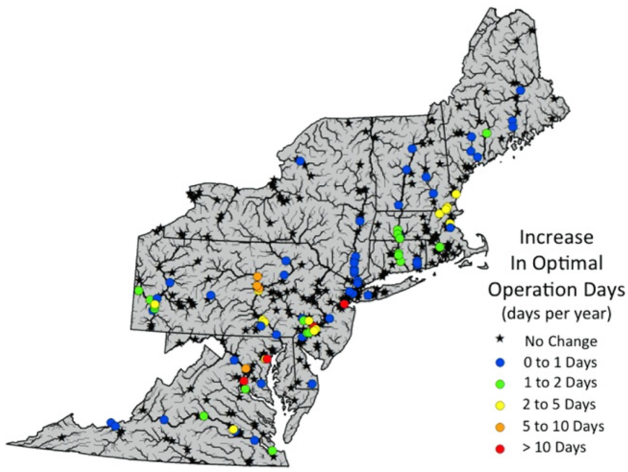

Figure 4. Average increase in the number of optimal operation days (days with intake river temperatures below 22 °C) per year at OTC plants due to the upstream ecosystem service of heat dissipation. Data shown were quantified by comparing scenarios with and without dissipation of upstream power plant heat over the 11 yr model period.

Northeast basins (table 1). The relatively high concentration of heat inputs in the Hudson and James Rivers (table 1) are likely because plants in these systems rely heavily on the additional dilution capacity provided by tidal water that our model does not account for. To better understand the spatial distribution of heat inputs, for each drainage network we calculated the average flow path distance from OTC and RCC power plants to the river mouth, weighted based on energy production (table 2). The average weighted distance to the ocean for OTC power plants in the Connecticut River basin (134.9 km) is the longest of those studied in the Northeast, whereas the Hudson has the shortest average weighted distance (55.8 km). These patterns heavily impact total network heat retention (table 1) and offset the fact that both the Connecticut and Hudson Rivers are in cooler northern areas of our regional domain. Thermoelectric plants in both of these basins predominantly use OTC technologies and rely extraordinarily on rivers as horizontal cooling towers, releasing over 48% of the total annual waste heat generated to the river system (figure 2).

Re-circulating cooling towers are highly effective in preventing anthropogenic heat from passing into the river network (table 1). A full 100% per cent of the total net annual electricity sector heat inputs to the river system are from power plants that use OTC technologies (table 1). Water temperatures of blowdown, the effluent from RCC towers, typically have a negligible affect on river temperatures (Miara and Vorosmarty 2013) but are shown here to be cool enough to result in a small net heat loss from the river systems. Cold effluent from RCC plants is enough to reduce average summer and even winter water temperatures in a few tributaries, but not in the larger main stem rivers (figure 3).

4. Impacts on aquatic ecosystems

The environmental costs associated with utilizing river networks to dissipate heat are reduced flow (from RCC and OTC) and increased freshwater river temperatures (from OTC). Total water withdrawals for thermoelectricity in the Northeast are substantial, corresponding to 11.8% of average

Table 3. Increases in unsuitable thermal habitats for various fish species in river segments downstream of thermoelectric plants. The total length of all river segments downstream of plants is 7530 km.

Fish species		Maximum average weekly tolerance[a] (°C)	Unsuitable habitat without thermoelectric plants considered (km)	Increase in unsuitable habitat due to thermoelectric plants (km)	Per cent increase in unsuitable habitat (%)
Brook trout	*Salvelinus fontinalis*	22.4	7526.6	3.9	0.1
Rainbow trout	*Oncorhynchus mykiss*	24.0	7451.1	45.5	0.6
Longnose dace	*Rhinichthys cataractae*	26.5	6100.1	191.8	3.1
Creek chub	*Semotilus atromaculatus*	27.1	5712.9	240.3	4.2
Northern pike	*Esox lucius*	28.0	5260.9	227.8	4.3
Walleye	*Stizostedion vitreum*	29.0	4687.1	461.1	9.8
Smallmouth bass	*Micropterus dolomieui*	29.5	4275.3	648.3	15.2
Bluntnose minnow	*Pimephales notatus*	30.1	3852.7	708.7	18.4
Golden shiner	*Notemigonus crysoleucas*	30.9	3177.5	773.4	24.3
River Carpsucker	*Carpiodes carpio*	32.1	2293.8	906.5	39.5
Red shiner	*Cyprinella lutrensis*	34.0	1452.8	782.5	53.9
Largemouth bass	*Micropterus salmoides*	35.5	917.6	738.6	80.5

[a] From Eaton and Scheller (1996).

annual flows (ranging in basins from 0.7% to 42.9%) and 22.6% of average summer flows (ranging from 1.1% to 95.1%), though most of these are non-consumptive (table 2). OTC dominates water usage, representing 98.0% of total annual and summer withdrawals by the sector. The range in water withdrawal during dry years (i.e. 2001) is considerable, ranging from 1.1% (Penobscot River) to 223% (James River) of total freshwater summer flows. Increased water temperatures and consumption of river discharge can both degrade natural habitats, especially during summer periods when flows are naturally low (Schindler *et al* 2005, Caissie 2006).

RCC withdraws substantially less than OTC technologies, but is nearly three times more consumptive, representing 74.1% of the total water consumed by thermoelectric plants in the region. Evaporative losses are minor in proportion (0.5%) to the average summer flow conditions in all basins in the northeast (table 2). The Delaware River experiences the greatest reductions in flow due to power plant consumption, losing 2.1% of average summer discharges. Water consumption during the driest year (2001) corresponds to 2.9% of summer flows in the Delaware River, but only 0.7% of summer flows for all basins draining to the Atlantic and implies evaporative water use by the thermoelectric sector is appropriate in this region relative to its hydrologic regime. Thus, our study aligns with earlier analyses (Averyt *et al* 2011) on the impact of thermoelectric stress on water supply in the northeast: the flow regime is minimally affected by power plants in the region on average, and we found only slightly more impact during dry years.

In contrast, heat inputs via OTC alter the temperature regime, sometimes over great distances. To identify the signature that thermal pollution has on water temperatures, simulations were conducted with and without TP2M activated. Heat inputs from thermoelectric power plants increase average summer and winter water temperatures by at least one degree in 25.7%, and 16.7% of potentially impacted river length (segments downstream of OTC and RCC plants which total 7530 km) in watersheds that drain to the Atlantic. Localized temperature increases can be extreme, especially in the winter (up to 27.0 °C) but are quickly diluted or dissipated. Impacts are lower but more widespread in the summer (figure 3). Peak temperature increases due to power plants are more significant in the winter due to the large difference in effluent and ambient temperatures but re-equilibration during cold months is rapid because heat dissipates quickly to the atmosphere over short flow path distances. Rivers are more effective at temperature re-equilibration during the winter than in the summer despite higher flows that would otherwise reduce their effectiveness at re-equilibration (Wu *et al* 2012). Slower dissipation of anthropogenic heat loads during the summer means that minor disturbances often propagate great distances downstream. This is most notable along the Connecticut River downstream of the Vermont Yankee power plant (located in the southeast corner of Vermont) where water temperatures due to thermal pollution are perturbed more than 1 °C over a short distance in the winter, but extend over the entire length of Massachusetts in the summer (figure 3).

Increased freshwater temperatures due to anthropogenic heat loads pose risks to the thermal habitat of native fish in the region. We conducted a simple analysis of impacts to fish thermal habitat similar to that of Mohseni *et al* (2003). The fish and temperature database matching system (Eaton *et al* 1995, Eaton and Scheller 1996) was used to define maximum average weekly temperatures tolerated by select cold, cool, and warm water fish species (table 3). Unsuitable habitat was defined on an annual basis as grid cells with maximum average weekly temperatures that exceed the maximum thermal tolerances for each species (Mohseni *et al* 2003). We quantified the total unsuitable habitat in all river lengths downstream of OTC and RCC for pristine (without TP2M) and contemporary (with TP2M) scenarios.

An increase in total unsuitable thermal habitats in rivers due to power plant discharges is apparent for all species considered (table 3). But, perhaps counterintuitively, power plant thermal pollution has a greater impact on the potential thermal habitat of warm water, rather than cool and cold-water fish. This is because, in our study region, conditions are already marginal for cool and cold-water fish in large rivers, and these species find refuge in headwaters and low-order streams (Hudy *et al* 2008) that do not receive power plant effluent. In segments downstream of plants, thermal pollution results in increases of 0.6%, 9.8%, and 53.9% in total annual river lengths where maximum average weekly temperatures exceed 24 °C, 29 °C, and 34 °C, respectively. In some cases, thermal pollution raises peak summer water temperatures to levels above critical ecosystem thresholds (EPA 2011). These pockets of exceptionally warm temperatures (up to 46 °C in freshwater systems during extreme events) could cause severe disruptions in otherwise healthy ecosystems, and the magnitude of these impacts is just beginning to be documented (Hester and Doyle 2011). Warm areas along the river corridor during winter may also provide refugia for various warm water invasive species (Dukes and Mooney 1999, Durance and Ormerod 2007, Pandolfo *et al* 2010, Rosa *et al* 2012), further threatening native aquatic wildlife.

Regional (Kaushal *et al* 2010) and global (van Vliet *et al* 2011) water temperature analyses have identified increasing water temperatures that are correlated with rising air temperatures. Annual mean water temperatures in some large streams and rivers in the US are increasing at a rate between 0.009 and 0.077 °C per year (Kaushal *et al* 2010). Sensitivities of simulated global mean water temperatures indicate increases of 1.3 °C, 2.6 °C, and 3.8 °C for air temperature increases of 2 °C, 4 °C, and 6 °C, respectively (van Vliet *et al* 2011). If these reported temperature increases represent baseline changes due to warming climate, the increases due to thermal pollution quantified here would significantly exacerbate the problem in densely populated regions with increasing energy demands (Hojjati and Battles 2005, Wilbanks *et al* 2008). Sensitivity analyses using various policy, climate, and energy demand scenarios indicate potential changes in impact (Miara *et al* 2013).

5. Conclusions

Assessment of the interactions among different cooling technologies, aquatic ecosystem services, and aquatic ecosystem impacts are critical to identify the full costs and tradeoffs of electricity production (Bennett *et al* 2009). OTC and RCC technologies at thermoelectric power plants are dependent on natural ecosystem services in river networks to provide coolant and for conveyance and attenuation of heat loads. OTC power plants are responsible for 100% of the regional net waste heat input to the river network, and given their spatial distribution, most (88.7% or 935.2 PJ yr^{-1}) is delivered to the ocean. Thus, the general placement of OTC plants in the Northeast limits the ecosystem service provided by waterways to conveyance rather than mitigation of waste heat. Upstream siting of OTC plants results in greater attenuation of anthropogenic heat loads but longer impact distances, whereas downstream siting results in less freshwater impact but greater thermal loads to coastal zones. The benefit that OTC plants gain from upstream anthropogenic heat dissipation is small but may increase with future climate. Thermal habitat loss in river segments downstream of plants is considerable, and will be exacerbated with climate change on the horizon (Eaton and Scheller 1996, van Vliet *et al* 2011) and increasing energy demands.

OTC cooling technologies withdraw a substantial proportion of river flows and leave a moderate footprint on average seasonal river temperatures whereas RCC plants evaporate considerably more river discharge but appear to pose minor environmental concern due to the low proportions of average summer flows they consume. Thus from a purely aquatic ecosystem standpoint, RCC technologies are preferred in water rich regions as OTC plants and their reliance on horizontal cooling towers may put an unnecessary stress on aquatic ecosystems. However, RCC technologies have much higher total costs. Total capital costs, operating costs, the efficiencies of the two cooling technologies, and the ancillary costs associated with relying on horizontal cooling towers to buffer heat loads for freshwater and coastal environments must be considered to fully evaluate the tradeoffs associated with thermoelectric power plants. These tradeoffs will vary across regions depending on local climate. Despite having even higher capital and operating costs, alternative technologies such as dry cooling may be preferred from an aquatic ecosystem standpoint. Future management should also consider the geographic placement of plants in the river network to minimize environmental impacts given increasing electricity demands and warming climate.

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