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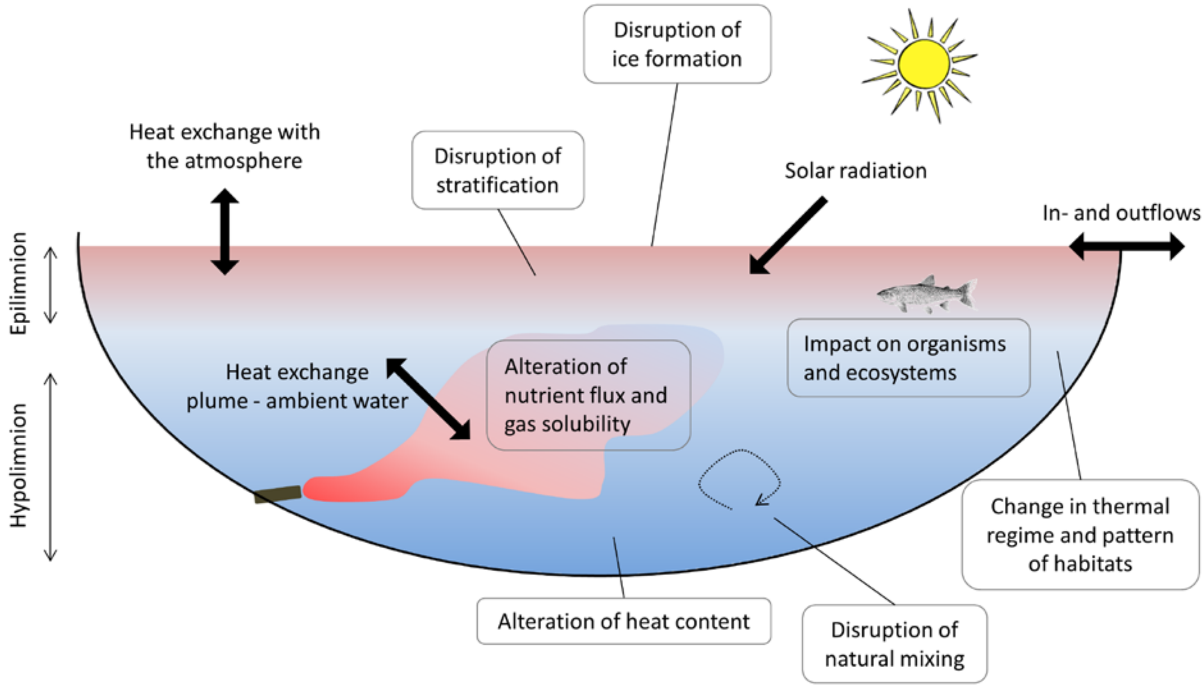
Abstract

The extraction and disposal of heat from lakes and rivers is a large yet scarcely exploited source of renewable energy, which can partly replace fossil fuel heating and electrical cooling systems. Its use is expected to increase in the near future, which brings attention to the impacts of discharging thermally altered water into aquatic systems. Our review indicates that thermal discharge affects

physical and ecological processes, with impacts recorded at all levels of biological organization. Many in-situ studies found local effects of thermal discharge (such as attraction or avoidance of mobile organisms), while impacts at the scale of the whole waterbody were rarely detected. In complex systems, diffuse impacts of thermal discharge are difficult to disentangle from natural variability or other anthropogenic influences. Discharge of warm water in summer is likely to be most critical, especially in the context of climate change. Under this scenario, water temperatures may reach maxima that negatively affect some species. Given the diversity and complexity of the impacts of thermal pollution on aquatic systems, careful planning and judicious management is required when using lakes and rivers for extraction and disposal of heat. We discuss the drivers that influence the severity of potential impacts of such thermal use, and the options available to avoid or mitigate these impacts (such as adapting the operating conditions).

Graphical/Visual Abstract and Caption



Using a waterbody for heating or cooling results in a discharge of colder or warmer water, which can affect the aquatic ecosystem.

INTRODUCTION

The ecological importance of temperature

Temperature is a key abiotic property of waterbodies (Webb & Nobilis, 2007), influencing nearly all physical and chemical characteristics (Parker, Krenkel, & Stevens, 1970), with implications for biological processes. For instance, water temperature governs the rate of photosynthesis of aquatic plants, the breakdown of leaf litter by invertebrates, fungi, and microbes, as well as the digestion, reproduction, growth, and dispersal of fish (Cincotta & Stauffer, 1984; Sinokrot & Stefan, 1993; Broadmeadow, Jones, Langford, Shaw, & Nisbet, 2011). Consequently, water temperature plays a major role in determining the structure and function of lake and river ecosystems (Arora, Tockner, &

Venohr, 2016; Preece & Jones, 2002), with consequences for the delivery of ecosystem services, such as fisheries and the provision of drinking water (Caissie, 2006).

The temperature regime of lakes and rivers

Water temperature in lakes and rivers varies considerably across multiple spatio-temporal scales (Caissie, 2006). Energy exchange through the water surface is usually the dominant factor controlling the heat content of surface waters. As a consequence, near-surface water temperature follows the two main cycles also observed in the atmosphere: diurnal and seasonal (Sinokrot & Stefan, 1993).

The natural temperature regime of a lake is determined by interactions between atmospheric forcing (heat exchange between water and air), solar radiation, in- and outflows (rivers, groundwater, and runoff), geothermal forcing (heat exchange between water and earth), and lake morphology. As the density of freshwater varies with temperature (maximum density at ~4 °C), most deep lakes develop a seasonal pattern of thermal stratification. In summer, the surface layers (the epilimnion) become warmer and less dense relative to the deeper layers (the hypolimnion). During this period, vertical exchange through the thermocline, the zone of steep temperature gradient (typically around 1 °C m^{-1}), is strongly reduced. When the epilimnion cools in winter, temperature and density become homogeneous throughout the water column, allowing vertical mixing. In some lakes, inverse stratification occurs in winter, whereby temperature decreases towards the lake surface. In such cases, vertical mixing usually occurs in both autumn and spring. Vertical mixing is an important process to replenish oxygen consumed by decomposition of organic matter in the hypolimnion and transport nutrients into the epilimnion.

The temperature regime of a river is driven by interactions between various factors such as the source of the water, flow rate, regional climate, riparian and topographic shading, and streambed morphology (Caissie, 2006; Arora et al., 2016). Along its course, a river exchanges energy with the atmosphere, with the riverbed, as well as with groundwater. Mixing processes are stronger in rivers than in lakes due to the stronger water flow and associated turbulence.

Human influence on water temperature

Waterbodies have been exploited by humans for millennia, and many human activities directly or indirectly alter water temperature (Hester & Doyle, 2011), an effect referred to as **thermal pollution** (Table 1). Depending on the type of thermal pollution, its impact can be local or spread over a large area, with potentially severe cumulative effects. One form of thermal pollution is where lakes and rivers are used for extraction and disposal of heat in order to heat or cool infrastructure or industrial processes (**thermal use**; see following section) – for example residential and commercial buildings, nuclear and fossil fuel power plants (Langford, 1990). Thermal use generates thermally altered water, which must often be discharged into a waterbody (**thermal discharge**).

Other types of thermal pollution include thermally altered runoff from urban or agricultural areas, and the temperature effects resulting from forest harvest. These result in small alterations in river temperature within each river reach (Boyd, 1996), with potentially large accumulated effects throughout a catchment. Reservoir operations, that is water storage and controlled release, generate a combination of different thermal impacts. Water released from the deeper layers of a reservoir are often colder than natural river water. Reduced discharge in residual flow reaches results in shallow and slow-flowing rivers that are less buffered against external forcing such as solar radiation (Caissie, 2006; Webb & Nobilis, 2007). Alterations of river morphology also influence the thermal dynamics of rivers. For example, channelized rivers are generally deeper and flow faster. As a result, residence time is shorter, leading to reduced influence of external forcing. Climate change is also a type of thermal pollution affecting the temperature of most aquatic ecosystems throughout the world.

Table 1. Human activities causing thermal pollution of lakes and rivers. Thermal use of waterbodies is linked to thermal discharge. The column "Degree of alteration" indicates the maximum magnitude of temperature change, based on the available literature and independently of its spatial extent – low: up to 3 °C, medium: up to 6 °C, large: up to 12 °C.

Source of thermal pollution	Spatial effect	Direction of alteration	Degree of alteration
Thermal discharge (Langford, 1990)	Point	Warming and cooling	Large
Wastewater effluents (Kinouchi, Yagi, & Miyamoto, 2007)	Point	Warming in winter, cooling in summer	Medium
Agricultural drainage (Blann, Anderson, Sands, & Vondracek, 2009)	Point	Generally warming	Low
Mine drainage, for example from passive treatment	Point and diffuse	Warming and cooling	Medium
Urban runoff (Nelson & Palmer, 2007)	Point and diffuse	Generally warming	Medium
Water abstraction, for example for hydropower production (Frutiger, 2004)	Diffuse	Warming in summer, cooling in winter	Medium
Water release, for example from reservoir operations (Frutiger, 2004)	Point	Warming in winter, cooling in summer	Large
Alteration of river morphology, for example channelization (Caissie, 2006; Poole & Berman, 2001)	Diffuse	Warming and cooling	Medium
Change in riparian shading (Broadmeadow et al., 2011)	Diffuse	Warming and cooling	Medium
Climate change (Poff, Brinson, & Day, 2002)	Diffuse	Generally warming	Low

Scope of this review

The rapidly growing human population and rising need for renewable energy increase the demand for thermal use of waterbodies. This necessitates improved understanding of the associated risks (Coulter, Sepúlveda, Troy, & Höök, 2014) in order to minimize negative impacts on ecosystems and guarantee the availability of water as a resource for multiple human uses (Hunziker & Wüest, 2011; Stewart et al., 2013). Our narrative literature review focuses on the physical and ecological impacts of thermal use of lakes and rivers, including both thermal and non-thermal impacts. Oceans and groundwater are not considered.

We start with an overview of the principles and application of thermal use. We then summarize the impacts of thermal use on aquatic physics and chemistry, organisms, and ecosystem processes, based on published theoretical, observational and experimental research. The impacts of thermal use are the result of complex interactions between operating conditions and ecosystem processes, making quantitative comparisons of studies difficult. We therefore focus more on a qualitative synthesis. Studies dealing with the impacts of other types of thermal pollution in aquatic systems (Table 1) are outside the scope of this review and not comprehensively reviewed. However, we refer to such studies where the described impacts are relevant for the assessment of the impacts of thermal use. We conclude with a synthesis of the main findings and considerations for management.

THERMAL USE OF LAKES AND RIVERS

Principle

Waterbodies represent natural heat reservoirs, which absorb solar and atmospheric heat over spring and summer, and release it to the atmosphere over winter. The temperature regime of waterbodies makes them suitable for thermal use in many parts of the world.

In the case of heat extraction, heat pumps mechanically extract thermal energy from lake or river water and warm another fluid (usually water) to higher temperatures. This fluid is then used to heat interior spaces, domestic water or infrastructure or to provide heat for industrial processes. Heat pumps can be operated with source water as cold as 3 °C. However, their efficiency – the heat output in comparison to the input of mechanical energy – increases with the temperature of the source water. The energy input to operate the heat pump is typically four to six times lower than for electrical heaters.

In the case of heat disposal (i.e., water used for cooling), many waterbodies are sufficiently cold to provide direct cooling by simply circulating the water through interior spaces, infrastructure or industrial processes. Temperatures < 15 °C are appropriate for most cooling applications (e.g., air conditioning, energy production, computer centers). Advanced cooling techniques allow the use of warmer water and recycling of used water. An example of such a technique is the use of channels or ponds, where heated water releases heat to the atmosphere before being discharged or reused for cooling (Manjunatha, Bobade, & Kudale, 2015). A more effective method is the operation of cooling towers, which dissipate most of the waste heat by evaporating water and thus reduce the amount of water and heat discharged into the waterbody as compared to direct cooling (Stewart et al., 2013).

Using water for heating therefore results in a cold thermal discharge (i.e., discharged water is colder than intake water), while using water for cooling results in warm thermal discharge (i.e., discharged water is warmer than intake water).

Present and future application

The potential for thermal use of waterbodies has not yet been widely exploited, even though the required technical knowledge is well established. River water has long been used for the cooling of power plants, while thermal use of lake water, and using waterbodies for heating, are less common. There is, however, growing interest in the vast potential offered by oceans, lakes, rivers and groundwater for domestic and industrial heating and cooling throughout the world. These renewable, reliable and local energy resources could significantly reduce the quantity of fossil fuels being burnt for heating worldwide. In addition, cooling from waterbodies could yield important reductions in electricity consumption, as it allows supplementing or replacing energy-intensive air-based chillers. As an example, heating and cooling from Lake Constance (Switzerland, Germany and Austria; volume: 48 km^3, mean depth: 90 m) in Central Europe with a heat extraction and discharge of 1 GW (i.e., 2 W m^{-2}) would be sufficient to supply energy for about a million people, assuming a heating and cooling demand of 1 kW per capita (Fink, Schmid, & Wüest, 2014). Modeling predicted that such thermal use would change the temperature of horizontally-averaged depth slices by < 0.2 °C (Fink et al., 2014).

IMPACTS OF THERMAL USE OF LAKES AND RIVERS

Current state of research

The thermal impacts of using river water for cooling have been broadly documented (Levin, Birch, Hillman, & Raines, 1972), whereas less information is available for lakes, except for the case of Lake Stechlin in Germany (Koschel et al., 2002; Box 2). The majority of studies of thermal use were conducted in the 1970s and 1980s (Souchon & Tissot, 2012) and investigated the ecological impacts of large temperature increases of up to 15 °C, typically resulting from power plant cooling (Brezina, Campbell, & Whitley, 1970; Langford, 1990). Less information is available on the impacts of smaller increases, that is < 1 °C in lakes and < 3 °C in rivers. In these cases, it is difficult to disentangle the effects of temperature from those of other stressors (Langford, 1990; Mathur, Robbins, & Purdy Jr., 1980). The impacts of using waterbodies for heating have also been scarcely studied. There is however a large and fast-growing literature on the impacts of other types of thermal pollution in waterbodies (Table 1), particularly of climate change. Research into ecosystem changes resulting from climate warming provides an indication of large-scale impacts that might be expected from warm thermal discharges. This source of information is important given that thermal use is not yet widespread and consequently research into its whole-ecosystem impacts is rather limited.

Thermal impacts on physical processes

Thermal use results in both thermal impacts, related to the temperature alteration caused by thermal discharge, and non-thermal impacts, for instance due to translocation of water (and nutrients), release of contaminants, or modification of flows and currents. We review the thermal and non-thermal impacts on the physical and ecological processes in lakes and rivers.

Lakes

Thermal discharge can have various impacts on the physics of a lake (Figure 1):

(a) *Altered temperature near the outlet*. In lakes and reservoirs, a thermal discharge forms a thermal plume. The temperature change is greatest in the immediate vicinity of the outlet, and the plume approaches the temperature of the ambient water as it disperses from the outlet, becoming gradually diluted by the entrainment of ambient water (Langford, 1990; Parker et al., 1970). It has been reported that the temperature alteration caused by a thermal discharge may be very strong in the discharge area (difference >5 °C) but non-measurable in the rest of the lake (Hickman, 1974; Neill & Magnuson, 1974). Thermal discharge may also locally increase thermal variability, resulting in faster temperature changes and a wider range of temperatures than would be present under the natural temperature regime (Thome et al., 2016).

(b) *Large-scale temperature alterations*. Intense thermal use can have a measurable effect on the heat content of an entire lake or lake zone. For example, a thermal discharge of 700 MW in the main tributary ~19 km upstream of Lake Biel (Switzerland; volume: 1.1 km^3, mean depth: 29 m), corresponding to a heat input to the lake of 18 W m^{-2}, was modelled to raise the mean temperature of the lake by 0.3 °C. In particular, thermal discharge in distinct zones of a lake (e.g., a subbasin or the hypolimnion) can accumulate until exchange occurs (e.g., through wind-induced or convective vertical mixing) (Kirillin, Shatwell, & Kasprzak, 2013). On the contrary, temperature alterations in the epilimnion or in a shallow lake equilibrate more rapidly with the atmosphere (Langford, 1990). In lakes with residence times similar to or shorter than the duration of seasonal stratification (e.g., Lake Biel with 58 days), large-scale impacts of thermal discharge will be lower since the thermally altered water is transferred rapidly to the outflow, instead of accumulating in the lake throughout the season (Råman Vinnå, Wüest, & Bouffard, 2017).

(c) *Disruption of ice cover*. Warm thermal discharge can reduce the extent and duration of ice cover. This effect has been observed both in the vicinity of the discharge (Hickman, 1974) and across the entire surface of a lake (Casper, 1985), and is most pronounced if the thermal plume affects the epilimnion.

(d) *Altered thermal stratification and mixing*. Thermal discharge may increase the temperature difference between the epilimnion and the hypolimnion. This would intensify stratification (stronger thermocline) and subsequently reduce the exchange of oxygen and nutrients between the epi- and hypolimnion (Parker et al., 1970; Råman Vinnå et al., 2017). Thermal discharge may also inhibit, reduce or delay vertical mixing at the end of the stratification season. In the case of Lake Constance, modeling showed that these effects are strongest in the case of a warm thermal discharge at mid-depth or near the surface (Fink et al., 2014). Under this scenario, the modeling indicated a slight strengthening of the thermocline: a substantial thermal use with a heat input up to 4.4 W m^{-2} would extend summer stagnation by a few days (Fink et al., 2014). This is a minor temporal change compared to the natural variability and to climate-related effects (Fink et al., 2014). Extracting heat from the lake resulted in a slightly longer winter circulation period or had no effect on stratification, depending on intake and discharge depths (Fink et al., 2014).

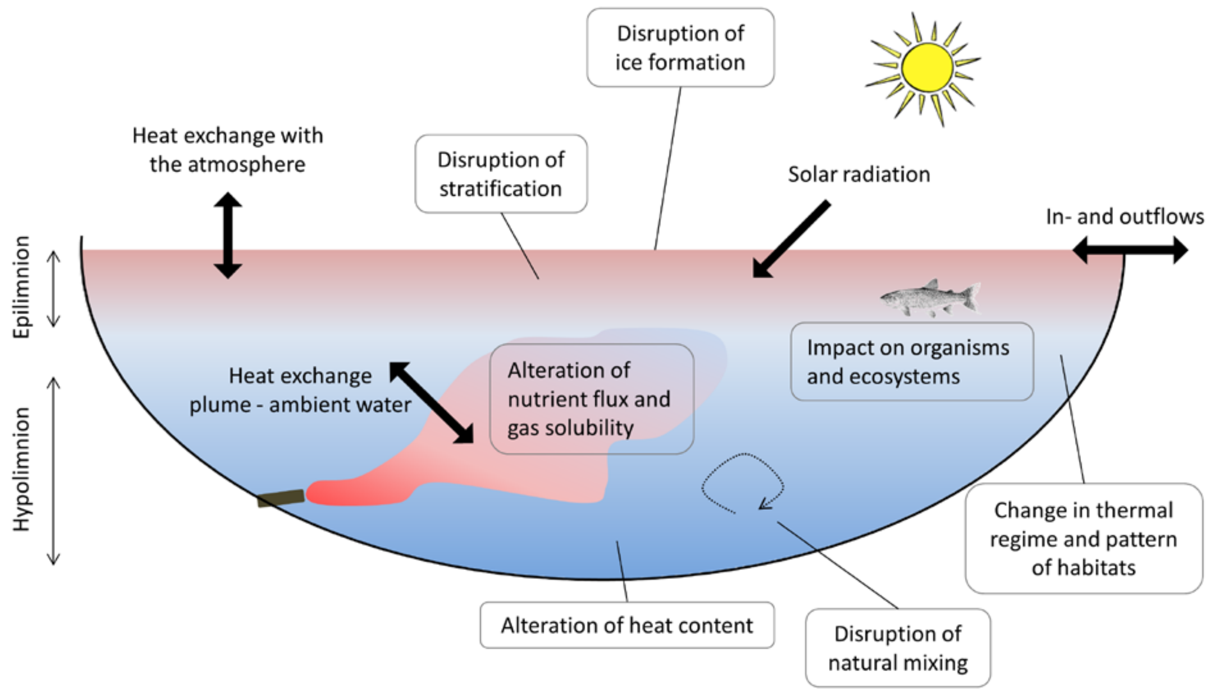


Figure 1. Key processes (unboxed) and possible consequences (boxed) of thermal discharge in lakes.

Rivers

Thermal discharge can have the following impacts on the physical characteristics of a river (Figure 2):

(a) *Altered temperature downstream of the discharge*. A river affected by thermal discharge becomes thermally heterogeneous, with temperatures sometimes differing markedly across the vertical and/or lateral dimensions for many kilometers downstream until the thermal plume is incorporated into the ambient water (Coutant, 1999; Prats, Val, Armengol, & Dolz, 2010; Bergé, 2012; Lugg & Copeland, 2014). The distance required for lateral mixing of the thermal plume increases with the river width, and decreases with increasing turbulence, which in turn depends on river morphology and discharge (Jirka & Weitbrecht, 2005). The thermally altered water can reach a downstream lake (Råman Vinnå et al., 2017) or ocean (Stewart et al., 2013). It may also permeate the groundwater (Molina-Giraldo, Bayer, Blum, & Cirpka, 2011), with thermal pollution then partly diffusing out of the river.

(b) *Disruption of river ice formation*. Early research showed that large, warm thermal discharge (above 1 GW), typically from power plants, could prevent ice formation during winter on river stretches over 20 km long (Dingman, Weeks, & Yen, 1968).

(c) *Density and plunging depth*. Through its effect on water density, a temperature alteration may shift the depth range at which a river enters a lake (Råman Vinnå et al., 2017). Rivers carry nutrients, oxygen and sediments, and altered delivery and distribution of these substances in a lake can have ecological implications, such as impacts on algal production.

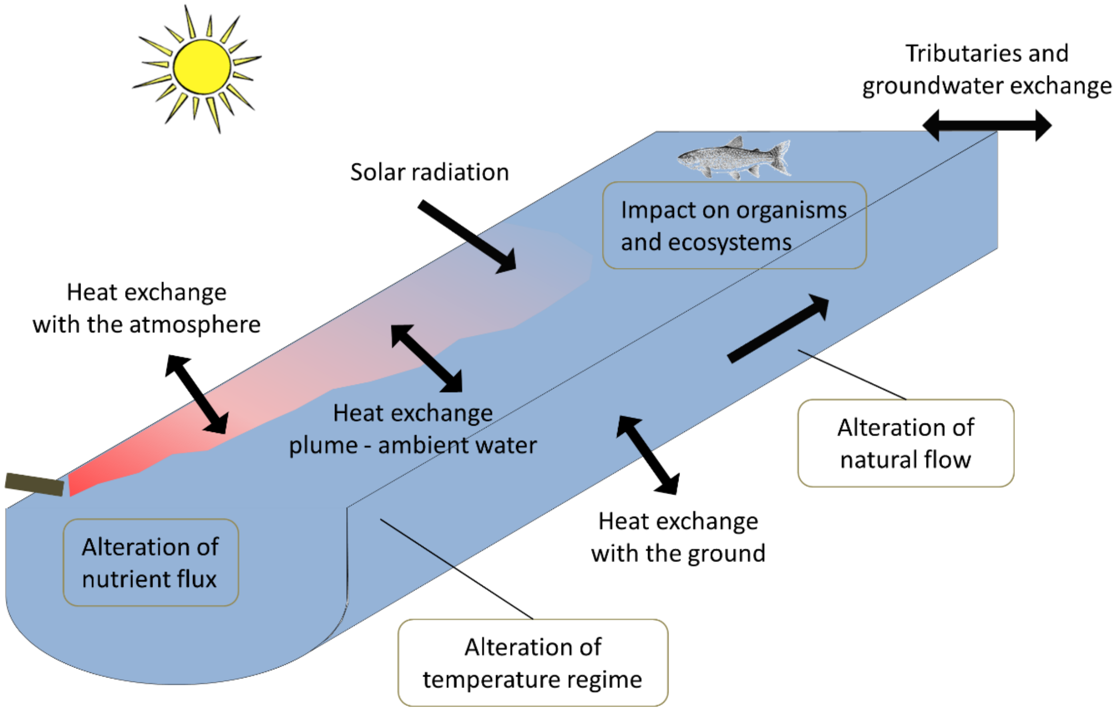


Figure 2. Key processes (unboxed) and possible consequences (boxed) of thermal discharge in rivers.

Thermal impacts on organisms and ecosystem processes

Responses of organisms to temperature alterations are determined by a combination of factors, including life stage, the exposure history of individuals and populations, species interactions (e.g., competition, predation, parasites, disease), and other environmental factors (e.g., oxygen, pH, pollutants) (Box 1).

Box 1. Temperature-related characteristics of aquatic organisms.

Thermoregulation. Many freshwater organisms such as fish or invertebrates are poikilotherms; that is their body temperature closely follows the ambient water temperature. Most physiological processes in poikilotherms accelerate as temperature increases. Warmer water therefore leads to faster metabolic processes, such as digestion (Langford, 1990). Low temperatures cause lethargy (Beitinger et al., 2000), with the organisms reacting slower to stimuli and feeding less (Küttel, Peter, & Wüest, 2002). Mobile organisms change location to remain in the temperature conditions that are most ecologically advantageous for their life stage (Coutant, 1999; Jobling, 1981). In addition, water temperature acts as a trigger for the timing of important biological processes, for example hatching, spawning and migration of fish (Mulhollem, Colombo, & Wahl, 2016).

Thermal tolerance. An organism has optimal temperature ranges for growth and reproduction (thermal niche), as well as lethal upper and lower bounds (thermal limits), which define the temperatures that will lead to death after a certain time (Langford, 1990; Figure 3). These temperatures depend on the life stage and vary seasonally (Khalanski & Gras, 1996). Generally, the thermal tolerance of an organism increases through its development, while spawning occurs within a particularly narrow range (Matousek, Stejskal, Prokesova, & Kouril, 2016). In addition, the thermal tolerance of organisms can be modified by various other factors: acclimatization (see below), oxygen and nutrient availability, presence of contaminants or parasites, interactions with other organisms, etc. (Coutant & Brook, 1970; Coutant, 1999). Interspecific competition for mutually preferred temperatures can shift or narrow the thermal niche of an organism (Magnuson, Crowder, & Medvick, 1979). Natural selection can additionally cause phenotypic and genetic adaptation of a population to local temperature regimes; an effect that is particularly common among salmonid fishes (Fraser, Weir, Bernatchez, Hansen, & Taylor, 2011). Because of the complexity of thermal tolerance, establishing universal thresholds for each species has proven extremely difficult, and inconsistent values are often found in the literature (Küttel et al., 2002).

Acclimatization. Within certain bounds on each side of their preferred temperature range, organisms acclimatize to gradual changes in ambient water temperature (Souchon & Tissot, 2012). This allows them to maintain normal performance at temperatures that would be stressful or even lethal if the temperature change occurred more suddenly (Jobling, 1981; Cincotta & Stauffer, 1984). Acclimatization can occur relatively rapidly, usually faster than 1 °C in 24 hours for fish (Fry, 1967), and can persist for a considerable length of time after exposure to the altered temperature has ceased (Boyd, 1996).

Response to temperature changes. In order of increasing severity, the direct effects of temperature on organisms can be classified as follows (Fry, 1967): (i) directive effects: behavioral responses, movements or migration; (ii) controlling effects: sub-lethal effects which affect physiological or biochemical processes of organisms, such as growth, metabolism or reproduction; (iii) lethal effects: temperature values which are deadly for an organism within a finite time.

As temperature shifts away from the thermal niche of an aquatic organism, stress steadily increases (Figure 3). The impacts of thermal pollution are thus most critical when temperature alterations occur close to the thermal limits of organisms (Heugens, Hendriks, Dekker, Straalen, & Admiraal, 2001), and particularly at higher temperatures (Hester & Doyle, 2011). Generally, thermal tolerance decreases with physiological and morphological complexity among poikilotherms (Hester & Doyle, 2011; Langford, 1990). Taking this into account, managing thermal pollution to minimize impacts on fish should also provide protection for most invertebrates, as well as for less complex organisms such as algae and bacteria (Bush, Welch, & Mar, 1974).

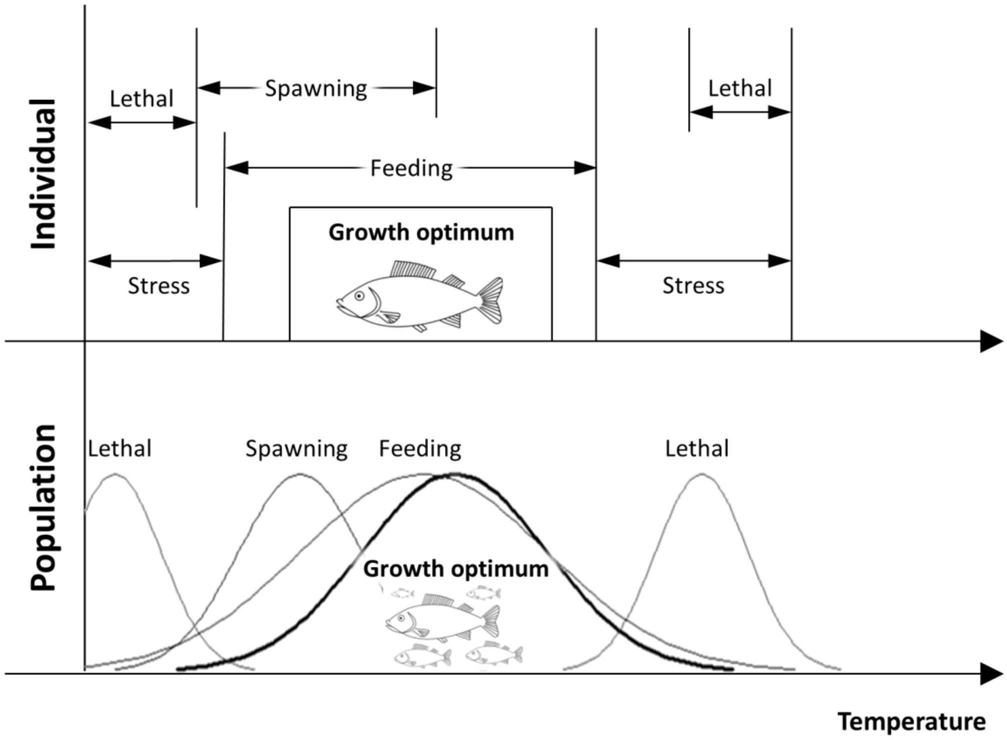


Figure 3. Exemplified thermal requirements of an individual and a population of a fish species. The curves in the lower plot represent the frequency distribution of the responses. Adapted from (Elliott, 1981).

Thermal pollution can modify behavior, metabolism, reproduction, growth, as well as community structure and abundance of all groups of aquatic organisms – bacteria, fungi, algae, phytoplankton, zooplankton, invertebrates and vertebrates (Langford, 1990). Impacts can take place at all levels of biological hierarchy and vary greatly between ecological communities (Levin et al., 1972). Important ecosystem processes may also be affected, such as ecosystem metabolism (e.g., primary production and respiration), nutrient cycling and trophic interactions (i.e., food web).The sensitivity towards temperature alterations varies strongly among ecosystems due to local adaptation of the populations and complex interactions among species (Mulhollem et al., 2016). Generally speaking, ecological impacts become more severe as the ratio between thermal pollution and natural temperature variability increases.

Table 2 summarizes the impacts of thermal pollution on organisms and ecosystem processes described in literature. In the following sections, we discuss the key impacts in more detail.

Directive effects: behavioral response of mobile organisms

Thermal discharge can cause mobile organisms to either avoid or aggregate in the affected zones (Coulter et al., 2014). This has been observed for phytoplankton (Winder & Sommer, 2012), zooplankton (Gehrs, Gibbons, & Sharitz, 1974), fish (Haynes, Gerber, & Buttner, 1989), amphibians, reptiles and mammals (Langford, 1990). For example, warm thermal discharge was found to locally increase fish abundance as fish aggregated around the discharge area, particularly in autumn, winter and spring (Langford, 1990). For example, a three-times-higher fish abundance was observed downstream of a power station raising the temperature of a river by nearly 7 °C on average (Sadler, 1980). Altered habitat use was also shown downstream of warm thermal discharges in a river in France, temperature clearly influencing the lateral distribution of fish (Bergé, 2012).

Several studies report that fish move to areas of colder water in lakes (Galloway & Kilambi, 1988) or migrate upstream in rivers (Caissie, 2006) during periods of exceptionally high temperatures. Particularly in summer, such zones of cooler water can play an important role in sustaining cold water fish populations in the vicinity of thermal discharge (Coutant, 1999; Lessard & Hayes, 2003; Caissie, 2006; Leuven et al., 2011). Zones of warmer water can also support mobile organisms in the context of a cold water discharge (Astles, Winstanley, Harris, & Gehrke, 2003). Such zones of water with temperature buffered against external thermal influences are called **thermal refuges**.

Biodiversity patterns: decline of temperature-sensitive taxa

Thermal discharges may result in local changes in the community composition of fish and other organisms. Among fish groups, salmonids (e.g., whitefish), generally prefer cooler waters compared to cyprinids and percids. As a consequence, they are more easily stressed by high water temperatures (Langford, 1990) and can experience higher mortality rates (Matousek et al., 2016). Decreased abundances of salmonids were reported close to warm water discharges with temperatures above 20–21 °C, which is warmer than the temperature range for optimal growth in this family (Haynes et al., 1989; Spigarelli, Thommes, Prepejchal, & Goldstein, 1983). Compared to other families, salmonids also show weaker competitive abilities and resistance to disease in warm water, which can reduce the area of habitat that they occupy (Isaak, Wollrab, Horan, & Chandler, 2012; Poole & Berman, 2001; Taniguchi, Rahel, Novinger, & Gerow, 1998). At higher temperatures, even comparatively heat-tolerant families may be disadvantaged. For example, within a thermal plume of particularly high temperature (discharge 20–34 °C, up to 10 °C above ambient), the activity of cyprinids (common barbel and chub) was strongly reduced (they were covering three times less distance), suggesting altered metabolism and swimming abilities (Bergé, 2012). Catfish appeared to be unaffected, due to their tolerance for higher temperatures.

In extreme cases, prolonged temperature changes resulting from thermal discharge can lead to a decline of native fish species and the establishment of generalist or alien species (Emde et al., 2016; Leuven et al., 2011; Lugg & Copeland, 2014). Competition with alien species can have negative repercussions on fisheries production based on native species (Eawag, 1981).

Phytoplankton communities in lakes were shown to be relatively robust to thermal discharge compared to other organisms, and rather influenced by nutrient conditions and predators (Langford, 1990; Mulhollem et al., 2016; Wilde, 1983). An increase in the ratio of green algae to diatoms can occur when thermal discharge increases the temperature above 25 °C (Coutant & Brook, 1970). Blue-green algae (cyanobacteria) are favored in even warmer waterbodies (Kosten et al., 2012) and may proliferate near warm thermal discharges, which can strongly affect water quality.

Ecosystem processes: productivity and timing of seasonal cycles

In most surface waters, particularly in cooler areas, increased temperature leads to increased primary productivity (Coutant & Brook, 1970; Ingleton & McMinn, 2012; Langford, 1990; Levin et al., 1972). Altered temperatures may also shift the timing of ecosystem processes, potentially leading to asynchrony between the life-cycle of organisms and seasonal patterns in other ecological components, such as resource and mate availability (Olden & Naiman, 2010; Thome et al., 2016). In lakes, temperature alterations can modify the timing and rate of algal growth (Langford, 1990) – for example, warming surface water was found to chronologically advance and amplify spring blooms of phytoplankton (Winder & Sommer, 2012; Mulhollem et al., 2016). Increased algal growth is counterbalanced by increased grazing by zooplankton and other herbivores, resulting in faster cycling of organic carbon and nutrients (Moore, Folt, & Stemberger, 1996; Pyka, Zdanowski, & Stawecki, 2013). Warm thermal discharges may also stimulate benthic algae (Ingleton & McMinn, 2012) and affect seasonal cycles of invertebrates by prolonging the reproductive period and accelerating development (Langford, 1990). Opposite impacts are expected from cold thermal discharges in the surface water (Eawag, 1981).

Other impacts

Warmer water can lead to a higher incidence of viral and fungal infections in fish (Langford, 1990). For example, the risk of proliferative kidney disease (PKD) in salmonids rises substantially if the temperature remains above 15 °C for several weeks, potentially causing high mortality and decline of salmonids (Burkhardt-Holm et al., 2005).

The solubility of oxygen in water decreases with increasing temperature, with potentially stressful effects for organisms. However, the change in oxygen solubility induced by thermal discharge is believed to be rather small (Coutant & Brook, 1970) and biologically insignificant (Neill & Magnuson, 1974; Pyka et al., 2013) – oxygen solubility is ~2 % lower in 1 °C warmer water. This is particularly the case in rivers, which are normally well oxygenated. Larger effects on oxygen concentrations in lakes could result indirectly if thermal discharge alters primary productivity or the intensity of vertical mixing.

Table 2. Review of studies describing the ecological impacts of thermal pollution.

	Ecological impact	Direction of alteration	Source of thermal pollution
Directive effects on organisms	Thermal avoidance or attraction for mobile organisms (e.g., altered use of thermal refuges)	Warming and cooling	Thermal discharge (Bergé, 2012; Brauer, Neill, & Magnuson, 1974; Coulter et al., 2014; Galloway & Kilambi, 1988; Gehrs et al., 1974; Grégoire, 1989; Haynes et al., 1989; Langford, 1990; Neill & Magnuson, 1974; Sadler, 1980; Worthington, Shaw, Daffern, & Langford, 2015)
			Climate warming (Winder & Sommer, 2012)
			Combined thermal discharge and climate warming (Leuven et al., 2011)
			Warm water release from dams (Lessard & Hayes, 2003)
			Cold water release from dams (Astles et al., 2003)
	Changes in feeding mode: shift towards a broader diet for fish (e.g., greater herbivory), higher predation on zooplankton, macrophytes and macroinvertebrates	Warming	Thermal discharge (Mulhollem et al., 2016)
			Climate warming (Jeppesen et al., 2010)
			Warm water release from dams (Lessard & Hayes, 2003)
			Experimental warming (Moore et al., 1996)
			Other sources (Brucet et al., 2012)
	Higher drift of benthic invertebrates	Warming and cooling	Warm or cold water release from dams (Carolli, Bruno, Siviglia, & Maiolini, 2012)

Controlling effects on organisms	Accelerated individual development of fish (particularly eggs and juveniles)	Warming	Thermal discharge (Grégoire, 1989; Thome et al., 2016) Climate warming (Isaak et al., 2012; Jeppesen et al., 2010)
	Adverse impacts on fish survival, growth, spawning and recruitment	Warming and cooling	Thermal discharge (Langford, 1990; Levin et al., 1972; Luksiene, Sandstrom, Lounasheimo, & Andersson, 2000; Thome et al., 2016) Warm water release from dams (Lessard & Hayes, 2003) Cold water release from dams (Astles et al., 2003; Lugg & Copeland, 2014; Preece & Jones, 2002)
	Higher winter survival and longer spawning and growing seasons for fish	Warming	Thermal discharge (Brezina et al., 1970; Langford, 1990; Levin et al., 1972) Climate warming (Jeppesen et al., 2010) Experimental warming (Moore et al., 1996)
	Increase in production and abundance of benthic organisms	Warming	Thermal discharge (Langford, 1990) Warm water release from dams (Lessard & Hayes, 2003) Other sources (Brucet et al., 2012)
	Increase in production and resiliency of zooplankton populations	Warming	Thermal discharge (Casper, 1985; Levin et al., 1972; Luksiene et al., 2000; Mathur et al., 1980)
	Advancement of spring phytoplankton bloom and increase in primary production	Warming	Thermal discharge (Grégoire, 1989; Hickman, 1974; Koschel et al., 2002; Levin et al., 1972; Mulhollem et al., 2016) Climate warming (Winder & Sommer, 2012)
	Stronger growth of harmful algae (cyanobacteria)	Warming	Thermal discharge (Hickman, 1974) Climate warming (Kosten et al., 2012)
	Modified metabolic activity, reproduction and abundance of bacteria and fungi	Warming and cooling	Thermal discharge (Langford, 1990)
Biodiversity patterns	Decline of temperature-sensitive taxa and cold water species; higher dominance of eurythermal species	Warming	Thermal discharge (Casper, 1985; Grégoire, 1989; Haynes et al., 1989; Levin et al., 1972; Spigarelli et al., 1983) Climate warming (Floury, Usseglio-Polatera, Ferreol, Delattre, & Souchon, 2013; Graham & Harrod, 2009; Heino, Virkkala, & Toivonen, 2009; Isaak et al., 2012) Warm water release from dams (Lessard & Hayes, 2003) Experimental warming (Moore et al., 1996) Other sources (Taniguchi et al., 1998)
	Replacement of native by invasive species	Warming and cooling	Thermal discharge and climate warming (Emde et al., 2016; Leuven et al., 2011) Cold water release from dams (Astles et al., 2003; Lugg & Copeland, 2014)
Ecosystem processes	Reduction in species biomass, density and mean body size (particularly for ectotherms)	Warming	Climate warming (Jeppesen et al., 2010; Winder & Sommer, 2012) Experimental warming (Moore et al., 1996)
	Increase in productivity and species richness	Warming	Thermal discharge (Coutant & Brook, 1970; Ingleton & McMinn, 2012; Langford, 1990) Climate warming (Jeppesen et al., 2010)

			Warm water release from dams (Lessard & Hayes, 2003)
	Time shift of seasonal cycles, possibly leading to asynchrony between life cycle and seasonal patterns (e.g., food availability)	Warming	Thermal discharge (Casper, 1985; Grégoire, 1989; Luksiene et al., 2000; Thome et al., 2016) Cold water release from dams (Preece & Jones, 2002) Reservoir operation (Olden & Naiman, 2010) Experimental warming (Moore et al., 1996)
	Eutrophication and deterioration of water quality	Warming	Thermal discharge (Pyka et al., 2013; Vandysh, 2009) Climate warming (Heino et al., 2009; Jeppesen et al., 2010) Experimental warming (McKee et al., 2003; Moore et al., 1996)
Other impacts	More frequent occurrence and faster spread of disease	Warming	Thermal discharge (Langford, 1990; Luksiene et al., 2000)
	Increased toxicity of contaminants	Warming	Thermal discharge (Langford, 1990) Other sources (Heugens et al., 2001)

Non-thermal impacts

Translocation of water and nutrients

The translocation of water to another depth or waterbody as a part of thermal use can, in itself, have ecological consequences, depending on the amount of water displaced (Chen, Weintraub, Herr, & Goldstein, 2000). For instance, during summer stratification, drawing water from the hypolimnion of a lake and discharging it into the epilimnion or outside the lake results in an increase of the relative thickness of the warm surface layer. Such operations can delay vertical mixing, as additional heat must be lost from the epilimnion before surface temperatures approach that of deeper water.

Where nutrients are limiting for biological growth, which is often the case in the epilimnion of lakes, a discharge of nutrient-rich water (e.g., from the hypolimnion) can have considerable ecological effects, such as an alteration of the trophic interactions. The impacts of anthropogenic alterations of nutrient loads on aquatic ecosystems can indeed be more severe than changes in temperature (Casper, 1985; Box 2). Such impacts include stimulation of algal blooms, increased productivity in the photic zone and consequently decreased water quality. Translocation of water can also have positive effects. For example, the discharge of aerated water into an anoxic zone of a lake could help to alleviate some effects of elevated nutrient loads and improve water quality.

Translocation of nutrients via thermal discharge may also affect the distribution of organisms. In Lake Monona in the USA, 4 to 10 times higher limnetic zooplankton concentrations were observed near a warm discharge (Brauer et al., 1974; Neill & Magnuson, 1974). Depending on diurnal and seasonal cycles, zooplanktivorous fish species (e.g., yellow bass, pumpkinseed, bluegill) aggregated around the discharge to take advantage of the higher food availability. Piscivorous species (e.g., longnose gar), were also attracted. While temperature was believed to be the main driver of local changes in the aquatic community, the above-mentioned aspects were specifically attributed to changes in the nutrient conditions and resulting species interactions (Neill & Magnuson, 1974).

Contaminants

Thermal use can have other ecological impacts through the release of contaminants from the associated infrastructure and its maintenance. In particular, release of additives (e.g., biocides such as chlorine, corrosion inhibitors or antifreezes) can be harmful for aquatic life (Langford, 1990), with possible impacts on organisms ranging from behavioral to lethal. Such effects are however normally confined to the area affected by the thermal plume (Grégoire, 1989). For example, a warm and chlorinated thermal discharge in India was shown, via field observations and laboratory experiments, to locally decrease phytoplankton abundance by 15-50 % and decrease productivity, most impact being attributed to chlorine (Poornima et al., 2005). Passive release of contaminants, such as metals due to the corrosion of the pipes, is usually considered too low to be ecologically significant (Langford, 1990).

Discharge velocity

Water velocity and turbulence influence the size of suspended particles, with slow-moving water mobilizing mostly the finer components of the sediment. A discharge entering a waterbody may locally scour and re-suspend fine sediments (Langford, 1990). The physical impacts of a discharge – for example, altered sediment particle size – are likely to be greater when the ambient water velocity is slower (Grégoire, 1989), which is particularly the case in lakes. Strong jets generated by the discharge create unnatural current conditions, which can disturb organisms and sediments. For instance, fish may mistake a near-surface discharge for a river inflow and try swimming against it, thus wasting energy (Langford, 1990).

A thermal plume in the surface layer could locally disrupt the formation of ice cover, because of the induced water currents (due to the discharge velocity or to the upwards convection of the plume). This effect can occur for both warm and cold discharges.

Box 2. Case study: impacts of thermal discharge in Lake Stechlin.

Study site. Lake Stechlin is a dimictic oligotrophic lake in Germany with a surface area of 4.25 km^2, a maximum depth of 68 m and a volume of 97.5 million m^3.The lake was heavily affected by a thermal discharge from a nuclear power plant between 1966 and 1989. Water quantities of ~300,000 m^3/day were taken from neighboring Lake Nehmitz and discharged into Lake Stechlin, with a temperature increase of ~10 °C (Casper, 1985). Lake Stechlin is the most extensively studied case of thermal discharge to a lake in scientific literature.

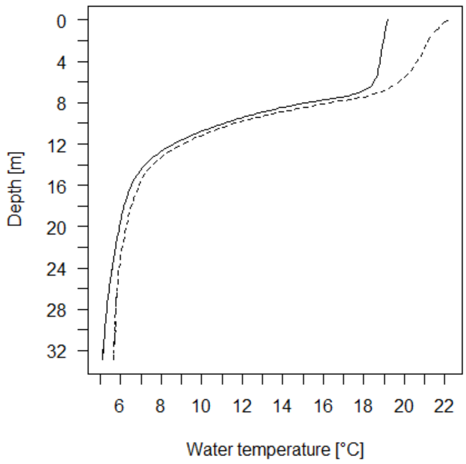


Figure 4. Mean temperature profile in Lake Stechlin in August before (—) and during (- - -) thermal use. Reproduced from (Casper 1985).

Physical and chemical processes. On average in winter, the whole lake was warmed by 1 °C (Casper, 1985). The temperature increase varied among seasons and throughout the water column: the epilimnion was especially affected in summer (Figure 4), when it was separated from the layers below by the thermocline, while the hypolimnion received most additional heat during vertical mixing. The distribution of the thermal plume at the surface was dependent on wind conditions. Heat fluxes to the atmosphere, mainly by evaporation, increased significantly, eliminating most of the heat added by the thermal discharge (Casper, 1985). Stratification was prolonged in summer, inverse stratification weakened or disappeared in winter, and ice cover was reduced (Kirillin et al., 2013). Decreased oxygen concentrations were believed to have been caused by extra nutrients translocated from Lake Nehmitz to Lake Stechlin. Discharged heat partly counteracted these negative effects by extending the autumn and spring circulation periods due to weaker winter inverse stratification (Casper, 1985). Thermal use may have contributed to the lower oxygen concentrations at the end of summer, as the warming extended the period of stratification.

Community composition and ecosystem processes. The discharge of the power plant is believed to have increased primary production, especially phytoplankton growth (Koschel et al., 2002). This impact was partly due to increased nutrient concentrations, although the lake remained oligotrophic (it had a more mesotrophic character for a short period some years near and after the end of the operation of the power plant) (Koschel et al., 2002). The composition of the phytoplankton community was initially disturbed, but returned to its previous state with continued operation of the plant (Casper, 1985). Macrophytes showed a similar reaction. Seasonal cycles were chronologically advanced in several organismal groups (e.g., by up to several months for periphyton; Casper, 1985) and earlier development and emergence of organisms was observed. Production of phyto- and macrozoobenthos was elevated during the cold season (Casper, 1985). Lethal effects occurred primarily when the temperature of the thermal discharge exceeded 25 °C in the warmer months (Casper, 1985). This caused a decrease in productivity and a higher mortality of organisms, the decomposition of which led to release of nutrients (notably phosphorus). As a counter effect, stronger summer stratification and shorter residence time helped to reduce the amount of organic material and nutrients entering the hypolimnion (Koschel et al., 2002).

Current state. Temperature and nutrient conditions in Lake Stechlin have returned close to the state before plant operation and the lake is known for its very clear water, low nutrient levels and low pollutants.

DISCUSSION AND OUTCOMES

Considerations for management

Several factors moderate the severity of the impacts of thermal use on an aquatic system. These factors comprise ecosystem characteristics (e.g., natural temperature regime), the extent of thermal pollution, type and operation of thermal use, mitigation measures, and additional anthropogenic stressors.

Natural temperature regime

The natural temperature regime of a waterbody can indicate its sensitivity to thermal pollution. Organisms living in waterbodies with a naturally high temporal temperature variability are likely to be less sensitive to thermal pollution (Sunday, Bates, & Dulvy, 2011). Spatial heterogeneity of temperature also offers thermal refuges, which can support the persistence of temperature sensitive species (Bisson, Dunham, & Reeves, 2009; Poole & Berman, 2001). Waterbodies with naturally lower spatial and temporal variability in temperature are therefore more vulnerable. In addition, impacts will likely be smaller if thermal pollution remains within the range of natural variability (for a given location and time in the year), than if conditions exceeding the natural temperature range are created. Consequently, seasonality should be considered when managing thermal use (Ingleton & McMinn, 2012): for example, warming is likely to be more critical in summer than in winter.

However, most current legislation addressing thermal pollution of waterbodies do not consider the natural temperature regime and its variability. Instead, they define absolute upper and lower limits that the temperature of the waterbody should not exceed, and sometimes maximum allowed temperature changes. Only a few countries acknowledge zonation of river fish communities. For example, the Swiss Water Protection Act states that (i) a thermal discharge may not change the temperature of a river by more than 3 °C, but only 1.5 °C in rivers where trout is considered a key species; and (ii) the resulting temperature may not exceed 25 °C. The diversity of aquatic habitats require legislation which takes into account this natural variability and the relative vulnerability of the affected ecosystems (Heino et al., 2009).

Severity and spatial extent of thermal impacts

The severity of local impacts of a thermal discharge (i.e., ecological changes in the direct vicinity of the outlet) is primarily determined by the difference in temperature between the ambient and discharged water. The spatial extent of the impacts of a thermal discharge (i.e., the rate at which the local impacts diminish with distance from the outlet) is determined by a number of factors, which vary between lakes and rivers (Table 3).

Table 3. Factors influencing the spatial extent of the impacts of a thermal discharge.

Lakes	Rivers	Comments
Total amount of heat extracted or disposed relative to the lake volume or river flow rate		A larger amount of heat exchanged via thermal discharge results in a larger area/volume more strongly affected by the thermally altered water (Galloway & Kilambi, 1988; Prats et al., 2010).
Operating conditions and design of outlets		See corresponding paragraph in the text.
Water currents (e.g., wind-induced)	Flow velocity	Faster currents or flow velocity (i.e., higher turbulence) increase the rate at which thermally altered water is transported away from the outlet (Hickman, 1974).
Stratification and vertical mixing	-	Stronger stratification and infrequent vertical mixing reduce the volume into which thermal discharge can spread, thus increasing local temperature alteration.
Morphology, residence time	Morphology, mixing with other rivers	A temperature alteration will equilibrate more quickly with the atmosphere in a shallow lake or river compared to a deeper one with the same volume or flow rate. A short residence time or the inflow of tributaries also accelerates heat dilution.
Local weather		Air temperature is a key factor for the heat exchange between the waterbody and the atmosphere (Schmid, Hunziker, & Wüest, 2014). Wind influences mixing and transport of heat away from the water surface (Brezina et al., 1970).

Local impacts of thermal discharge are much easier to detect than large-scale impacts, which are generally weaker or undetectable (Grégoire, 1989; Langford, 1990; Worthington et al., 2015). Thermal discharge can cause a local temperature alteration, resulting for example in attraction or avoidance of mobile organisms (Grégoire, 1989) or establishment of invasive species (Emde et al., 2016). This can occur without any marked large-scale impact on the aquatic ecosystem, even in the case of a large temperature difference between discharged and ambient water (Brezina et al., 1970; Casper, 1985; Haynes et al., 1989; Poornima et al., 2005; Worthington et al., 2015).

Operating conditions and design of outlets

The thermal use infrastructure influences the spatial extent of thermal discharge and thereby the severity of the potential ecological impact. Above all, the temperature difference between the intake water and the thermal discharge is determined by the design and operation of the heat exchangers. For the extraction or disposal of a given amount of heat, one may operate with a lower temperature difference (and therefore larger flow rate) or a higher temperature difference (and therefore lower flow rate). The choice should depend on which is expected to have the lower impact: the translocation of large volumes of water or high local temperature alterations. Modeling also suggests that using water for both cooling in summer and heating in winter reduces the mean thermal change throughout a lake (Fink et al., 2014).

The location and design of the outlet influences the dispersal of the thermal plume. Particularly in lakes, the depth of the discharge relative to the thermocline, as well as the velocity and angle of discharge, determine the dispersal capacity of the plume. Local impacts of thermal discharge on the temperature regime can be reduced by minimizing the temperature difference between discharged and ambient water, for example, extracting deep, cold water in summer and discharging the heated water in shallower, warmer layers (Fink et al., 2014; Langford, 1990). In general, discharging water into a shallow lake or near the surface of the waterbody promotes faster thermal equilibration with the atmosphere (Fink et al., 2014; Langford, 1990), and reduces the overall heat load in the receiving waterbody (MacDonald, 2009). Faster mixing can be promoted by techniques such as premixing with ambient water. Spraying the discharge above the water also accelerates heat dissipation (Langford, 1990).

The planning of infrastructure with a large warm thermal discharge, or thermal use in areas with low water availability, should consider systems which cool and recycle part or all of the water, such as evaporative cooling (Grégoire, 1989; Langford, 1990). Such techniques significantly reduce water consumption and thus ameliorate the impacts of thermal discharge on aquatic ecosystems. For example, cooling towers can reduce water consumption by a factor of 30 and the discharged heat by a factor of 100 in comparison to direct cooling (Verones et al., 2010).

Mitigation measures

The rising use of lakes and rivers for extraction and disposal of heat means that water managers will be increasingly required to mitigate the effects of this type of thermal pollution. The impacts of thermal use can be partially mitigated by restoring other aspects of lake and river ecosystems towards their natural state. Examples include rehabilitation of impaired habitats, restoring or maintaining natural variability (e.g., in river flows) and thermal niches, reducing loads of anthropogenic nutrients and pollutants, conservation of riparian forests and removal of barriers to fish migration (Bisson et al., 2009; Isaak et al., 2012; Olden & Naiman, 2010; Orr, Johnson, Wilby, Hatton-Ellis, & Broadmeadow, 2015; Poff et al., 2002). In addition to regulations to guide, support and control thermal use, water management policy should consider facilitating the aforementioned actions. Ensuring the availability of thermal refuges also contributes to ameliorate possible negative ecological effects of thermal discharge, especially under extreme temperature conditions. For example, preservation of cooler flows (e.g., from groundwater or highland rivers) can help sensitive species in times of extreme heat.

Presence of other stressors

Aquatic organisms face a wide variety of anthropogenic stressors such as pollutants, sedimentation, habitat modification (e.g., lakeshore developments), habitat fragmentation (e.g., dams) and eutrophication. Thermal discharge therefore needs to be considered as one among many stressors, often with interacting effects (Heugens et al., 2001). For instance, an anthropogenically modified lake or river may lack the temperature variability necessary for mobile organisms to find adequate conditions and survive periods of extreme temperature (Hunziker & Wüest, 2011). This is highly relevant as the response of fish to thermal discharge can be largely influenced by the alteration of thermal refuges and migratory corridors (Poff et al., 2002).

Climate change

Climate change is predicted to cause major changes to aquatic systems in the 21st century (Poff et al., 2002; Box 3). In this context, any additional warming of water is likely to cause additional thermal stress to organisms and ecosystems. On the contrary, extracting heat from lakes and rivers and discharging the cooled water could partially counteract the effects of climate warming (Fink et al., 2014). For example, cold water discharge into the epilimnion of a lake reduces the temperature of this layer and could support vertical mixing.

Box 3. Climate change: warming rates and main physical impacts in lakes and rivers.

Warming rates. Climate change induces a global rise in water temperature, mainly through increased air temperature. Significant warming rates of summer surface temperatures of 0.0–0.8 °C/decade have been observed in most lakes throughout the world since 1985 (O'Reilly et al., 2015). The deep water temperature of several European lakes has also increased at a rate of 0.1–0.2 °C/decade during the second half of the 20th century (Dokulil et al., 2006). Stream and river temperatures were observed to increase by 0.09–0.77 °C/decade over the long-term in the USA (Kaushal et al., 2010).
Impacts on physical processes. Climate change places a significant thermal pressure on most aquatic ecosystems by increasing water temperature. Its effects include alteration of the physical, chemical and ecosystem processes, as well as of the geographic distribution of species (Jeppesen et al., 2010; Poff et al., 2002). In most lakes, climate warming is expected to intensify stratification, with negative impacts on deep water renewal and nutrient cycling (Kirillin et al., 2013). As a result, some lakes change their mixing dynamics, for example from dimictic to monomictic or from monomictic to oligomictic. In addition, climate warming can prevent the formation, reduce the extent and shorten the duration of ice cover. In most rivers, climate change may reduce the average flow rate, particularly during warm periods, which makes the rivers less buffered and more sensitive to warming (Arora et al., 2016; Poole & Berman, 2001; van Vliet, Ludwig, Zwolsman, Weedon, & Kabat, 2011).

CONCLUSIONS AND OUTLOOK

Thermal pollution resulting from thermal use affects the temperature regime of waterbodies, typically increasing the amplitude of seasonal cycles and increasing rates of temperature change. Thermal discharge can have direct impacts on organisms by modifying metabolic rates and behavior, as well as indirect impacts by altering ecosystem processes such as stratification. Different responses to thermal discharge among species and functional groups modifies ecosystem-level impacts and their effect on ecosystem services. Figure 5 offers a conceptual model synthesizing the impacts pathways of thermal discharge on (i) physics and chemistry, (ii) organisms and ecosystems, and (iii) ecosystem services in aquatic systems.

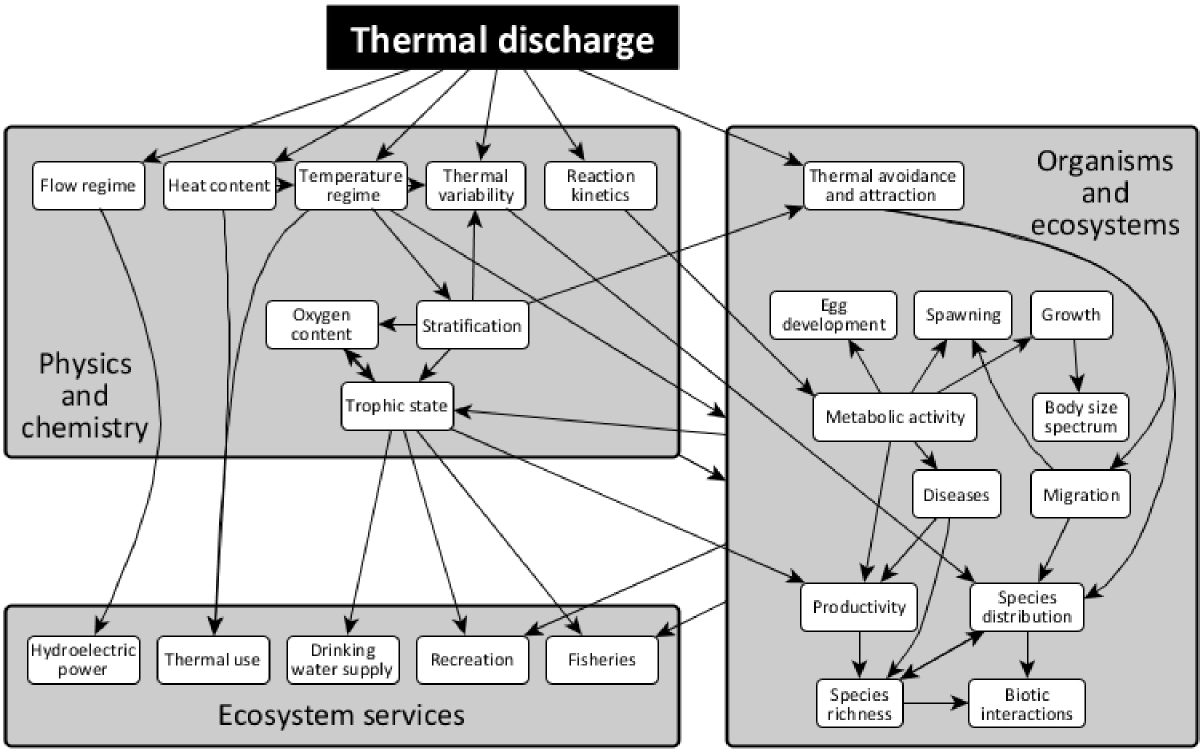


Figure 5. A conceptual model of the impacts of thermal discharge in lakes and rivers.

Many environmental parameters and processes influence the severity and extent of impacts of thermal discharge on aquatic organisms and ecosystems. Ecological effects of thermal discharge are likely to be most problematic in the case of warm thermal discharge in summer, as climate warming already sets organisms and ecosystems under stress on a large scale. The complexity of natural ecosystems means that responses to thermal use of waterbodies are difficult to predict, even with knowledge of thermal tolerances of individual populations. Ecological effects can be mitigated through placement of outlets and adaptation of thermal discharges based on knowledge of seasonal cycles in aquatic ecosystems. Given the many impacts of thermal use, the onus is on managers and policy makers to weigh up the severity and spatial scale of the impacts in aquatic ecosystems against the environmental impacts of other energy sources for heating and cooling.

This review highlighted several gaps in knowledge relating to thermal use of lakes and rivers (listed in Table 4). Further research should focus on improving our mechanistic understanding of the impacts of thermal use in the context of other forms of thermal pollution such as climate change, and in the presence of other stressors. Further research on this issue would increase the planning security for using lakes and rivers as renewable energy source, as well as improve mitigation measures. The complexity of this question requires a thorough approach with investigations based on theoretical aspects, modeling and in-situ observations.

In addition, future research should focus on the potential of thermal use for mitigation of the impacts of climate change. For example, heat extraction (resulting in cold thermal discharge) could locally counteract climate warming and possibly benefit ecosystems. Little research has been conducted in this regard, and the chances and risks of such mitigation measures are largely unknown.

Table 4. Open questions for research.

Topic	Example questions
Thermal dynamics of lakes and rivers	How fast and how far do thermal plumes distribute and dissipate? How does thermal discharge affect lateral and vertical heterogeneity in temperature in rivers?
Physical and biological impacts of cold water discharge in lakes	How is vertical mixing affected? To what extent can the impacts of climate warming be compensated? How is the natural temperature regime impacted throughout the year? What are "acceptable" limits of temperature alterations for ecosystems?
Ecological responses to thermal discharge	How do organisms respond to short-term changes caused by thermal discharge? Can local ecological effects near thermal discharge have large-scale impacts (e.g., warm water species surviving better through winter and then proliferating throughout the entire waterbody in spring/summer)? How can the sensitivity of specific aquatic ecosystems to thermal pollution be quantified?
Multiple stressors and cumulative impacts	How can the cumulative impacts of multiple forms of thermal pollution and other stressors (e.g., thermal discharge, climate change, hydropower production, residual flows, land use changes) within complex catchments be estimated?
Ecosystem services	How do alterations in water temperature affect the provision of ecosystem services (e.g., fisheries, provision of drinking water)?
Mitigation actions	What are appropriate strategies to reduce the impacts of warm thermal pollution in summer? How effective are these strategies (quantification)?

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