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Review Article
Thermal Pollution and the Aggravating Effects of Climate Change: Impact of Thermal Stress on Aquatic Ecosystems

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Abstract
Aquatic systems have increasingly being under anthropogenic perturbation. Thermal pollution and climate change are among the most important pressures affecting aquatic ecosystems. Anthropogenic pressures usually generate cumulative and synergistic effects. Information on cumulative effects is important to aquatic resources management, since they may affect human uses of these systems and impair management action plans to reduce hazards and environmental risks. The aim of this study was to synthesize literature on the effects of thermal pollution and climate change and their cumulative effects of thermal stressors on aquatic ecosystems, with the view to identifying the solutions, methodological challenges in study design, research needs and gaps in knowledge. Results have shown that cumulative effects of thermal stress tend to be more common compared to negative and antagonistic outcomes. Cumulatively, thermal pollution and climate change present an unprecedented challenge to the global aquatic systems, while the impacts are being felt globally, some regions will be more acutely affected than others. Thermal stress has altered aquatic ecosystems worldwide and the patterns of change observed in recent decades are expected to continue and worsen in the near future, if no meaningful steps are taken. The study concludes with a call for in-depth studies, if we must unravel the complex responses of aquatic ecosystems to thermal pollution under climate change scenarios.

Key words: Thermal stress, climate change, aquatic ecosystems, cumulative effects, global warming

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INTRODUCTION

Climate change has caused an approximate 0.8°C increase in global temperature between 1890 and 2009[1] and the average surface temperature is expected to rise by 1.0-3.7°C as a result of this trend[2,3]. The characteristic of water that indicates how warm or cold is its temperature. It represents the average kinetic energy of water molecules. The bulk of water's biological, chemical and physical properties as well as the ecological activities that take place in aquatic habitats are influenced by temperature.

Water absorbs and releases heat slowly, because of its high specific capacity, changing its temperature requires a significant amount of energy, this is one of the most peculiar and crucial properties of water. Because of this special quality, water bodies have been thought of as ways to dispose off heat and can be used for both heating and cooling. Throughout the eighteenth century, as the number of industries grew, water became an increasingly important coolant in many industrial processes. The requirement for cooling water grew as the industry expanded and became more diverse. Currently, approximately 80% of the water used by industries globally is utilized for cooling[1].

Large-scale environmental disruptions are unavoidable, when industrial facilities use practically the whole watercourse for cooling. The electric power industry is the largest user of industrial water, using billions of liters every day. Since the nineteenth century, scientists have documented an abnormal increase in global temperature as one of the debilitating effects of climatic change, caused by the release of carbon dioxide and other greenhouse gases into the atmosphere as a result of massive technological deployment in industrial processes and the use of fossil-based energy systems[1]. This has exacerbated thermal stress in aquatic habitats that have previously suffered from thermal pollution caused by anthropogenic disruption. Thermal stressors are harming numerous aquatic systems throughout the world. Several studies have shown that climate change is inextricably linked to the issues of water resource conservation and management[4,5]. Climate change has resulted in increased variability in global water systems, including disruption of water cycles, extreme weather events, unpredictability of water availability, declining water quality, threats to sustainable development, biodiversity loss and deprivation of the enjoyment of human rights to safe drinking water and sanitation worldwide[6].

Thermally stressed aquatic systems are biologically weak, incapable of sustaining and maintaining ecological balance and so unable to provide their inherent ecosystem services. Climate change is seen as a nonpoint source of thermal pollution affecting aquatic systems, posing a significant threat to humans and ecosystems[7].

Temperature is one of the most well recognised drivers of climate change, with global data indicating that temperatures have risen by more than 1°C during the late twentieth century[8]. Despite the apparent impacts of thermal pollution and the exacerbated effects of climate change on aquatic ecosystems, little attention has been dedicated to assessing the dangers to aquatic systems. The primary goal of this study was to conduct a literature search on the potential impact of thermal stress on aquatic resources, identifying the solutions, methodological challenges in study design and gaps in knowledge and research needs. This is because a thorough understanding of the impact of thermal stress exacerbated by changing climatic conditions on community structure and ecosystem functioning at various scales is critical for determining the best management strategies and the role aquatic systems can play in climate mitigation and adaptation.

Variations in water temperature: A variety of factors influence the regional and temporal patterns in water temperature. Temperature can vary geographically, longitudinally along the length of a water course, at the watershed size and on a finer scale, depending on geomorphic features of the habitat such as the existence of riffles, pools, backwaters, etc. The characteristics of catchment areas vary according to the climate, geography, topography and vegetation[9]. In a river system, longitudinal variation often occurs down the course, but it can also vary by site, with variance occurring literally across the channel and within ecosystems.

Water temperature trends in aquatic systems can vary both within and between water bodies. The temperature of a body of water at any time may differ based on its location, but, daily and seasonal patterns, on the other hand, are quite predictable in a specific location. In general, the lowest temperatures occur at night or early in the morning, followed by the highest temperatures in the afternoon, though seasonal variations and the size of the body of water might influence this[10].

Sources of thermal stress in aquatic ecosystems: A variety of human activities are known to alter water temperature in aquatic systems, creating a shift in temperature distribution and resulting in an increase or decrease in temperature regimes. Some of these activities are:

Heated discharges: Discharge of heated effluents, such as heated industrial waste, heated cooling water from power plants, returning irrigation water and groundwater, into a natural water body, raises the water temperature in the receiving aquatic system. The impact of heated discharge on aquatic ecosystems varies depending on prevailing weather conditions and how much hot effluent mixes with the receiving water[11]. The most harmful consequence happens when a coating of hot water covers the entire aquatic system. Heated industrial discharges frequently affect other types of pollution, such as chemical pollution, where the toxicity of compounds discharged with the heated water is known to rise dramatically[11].

Irrigation practices and the return of agricultural drainage can cause temperature to rise by 10 to 20°C[11]. Groundwater has a distinct thermal regime different from surface water, which is determined by geological and subterranean factors. When groundwater is used as a water supply and discharged into an aquatic system, the water temperature of the receiving water may be boosted or decreased.

Flow modification: Changes in water temperature may occur as a result of changes in natural flow caused by catchment regulation, inter-basin transfer and riparian vegetation modification. The degree of alteration caused by upstream impoundment on the downstream temperature regime is dictated by factors, such as the depth at which the release is done, discharge pattern, hydrological variables, such as retention time, stratification pattern and thermal gradients and the impoundment's location within the stretch of the water body's longitudinal extent. The effects may include a delayed seasonal temperature maximum, a rise in mean water temperature and a decrease in the rate of variability between temperature extremes[12].

During inter-basin transfer, a cold head water transfer to a warmer mid-reach will affect the recipient water body's temperature. Inter-basin transfer has been proven to have an impact on aquatic organisms in the recipient system, resulting in a shift in species and community composition. Riparian vegetation's change impacts the temperature of water bodies. When water bodies are exposed to more direct solar radiation, particularly when riparian vegetation that shadows a water body is eliminated, temperature differences become more pronounced. Riparian vegetation influences stream temperature in three ways[13], including the emission of long-wave radiation, the absorption of some incoming radiation and the formation of a microclimate.

Global warming and climate change: The increase in average global temperature due to anthropogenic influences has been widely reported. The major human activities leading to global warming include the combustion of fossil fuels and biomass, nuclear fission, forest destruction and the dumping of human and animal waste. If these activities continue unabated, aquatic systems are likely to continue experiencing remarkable shifts in temperature. The average annual increase in water temperature in aquatic ecosystems is anticipated to be between 2-5°C[2].

Importance of water temperature in aquatic systems: The temperature of water has a substantial impact on most ecological processes in aquatic ecosystems. Water temperature influences photosynthesis, respiration, growth rate, development and ecological interactions. Altered water temperature is a primary source of water quality degradation and has an impact on other water quality indicators. Measuring water temperature helps to determine the degree of variability in temperature swings, as well as the expected effects on water quality and ecosystem health. Temperature determines which creatures may dwell in watery habitats.

Aquatic creatures have a preferred temperature range; if temperatures rise too high or fall too low, the environment becomes unsuitable for the species. Temperature also has a substantial impact on water chemistry. Chemical processes often occur faster at higher temperatures. Higher temperatures allow water, particularly groundwater, to dissolve more minerals from the underlying rock, increasing its electrical conductivity[14].

Heat as a stress: Why is adding thermal energy to an aquatic system regarded as stressful for aquatic organisms? Stress is defined as any condition that disrupts ecological balance and prevents ecosystems from meeting the needs for self-regulation and natural ecosystem functions. In general, increased heat in water reduces the dissolved oxygen available to aquatic life, increases the solubility of metals and other toxins in water and may increase the toxicity of some pollutants to aquatic organisms and algal blooms[5,15].

Short-term temperature increases have the following effects on aquatic species: Reduced sexual maturation, inhibition of critical stages of larval development, reduced feeding, reduced growth, increased susceptibility to predation, increased incidence of disease and parasitism, increased migration and increased organism death. It also reduces aquatic productivity. Long-term temperature increases result in the loss of aquatic species whose survival and reproduction are temperature dependent; changes in the abundance and distribution of aquatic species; increased rate of surface water evaporation; increased salinity and shrinkage of waterbodies and habitat loss.

In addition to the foregoing, cooling water from nuclear-powered facilities may contain trace levels of radioactive elements, which may be concentrated in crop plants irrigated with such effluent and aquatic species[5].

Thermal stress as threat to aquatic ecosystems: Thermal pollution has serious repercussions for aquatic environments. At the individual organism level, temperature increases can be seen through physiological and behavioural effects; at the population scale, through individual development, reproduction and rates of survival and at the community level, temperature-tolerant organisms outnumber temperature-intolerant organisms, thereby bringing about changes in community structure[16,17]. In general, thermal pollution has two significant effects on aquatic ecosystems: Full decimation of aquatic biota caused by heat shock and migration of the biota to a more suited environment. Although species have temperature constraints on their survival abilities, most can acclimatise to some extent if temperature changes are moderate. The rapid transition is typically fatal.

The life cycle of many aquatic creatures is intricately tied to water temperature. Fish frequently select their habitat, migrate and spawn in response to temperature cues[18]. Some aquatic species spawn as the temperature decreases, whereas others spawn as the temperature increases. Shellfish, such as oysters, are so sensitive to temperature changes that they spawn within hours after reaching a threshold temperature[18]. It is known that Trout eggs take 165 days to hatch at 3°C, 32 days at 12°C and do not hatch at all above 15°C[19].

Also, it has been demonstrated that at higher temperatures, molluscs produce gametes indefinitely, resulting in little or no development, because all energy is directed toward gamete synthesis. This is consistent with the instance reported in Epe Lagoon, Nigeria, which receives heated water from an electric power station; surface water temperatures ranged from 29 to 43°C with an average of 38°C during a two-year period[20]. Temperature increases also disrupt the normal maturation and spawning cycles of molluscs[21]. Molluscs, for example, are programmed to go through a cycle of growth and reserve accumulation before converting to gametes and spawning. This impacts the rate of egg development and offspring growth, as well as the number of generations per year and the colony's efficacy.

Temperature changes also affect the longevity of aquatic creatures, for example, water fleas, such as *Daphnia*, survive for 108 days at 8°C, but only 29 days at 28°C[22]. Reproduction and development in mayflies, such as *Deleatidium* sp., have been proven to have a strong relationship with temperature[23]. In some species, ambient water temperature during larval growth is proportional to adult body size. Some species have unique temperature thresholds for growth, with no growth recorded until a certain temperature threshold is reached.

Life history coincidence has been reported to decrease towards the equator, indicating that univoltine life cycles are dominating in the arctic and cold temperate zones and growth is limited or interrupted for some periods of the year[23]. Univoltine life cycles dominate in moderate temperate climates, with year-round growth, but multivoltine life cycles dominate in the tropics. Reproduction, developmental rate and life history are all known to be substantially synchronous and strongly seasonal in the northern high latitudes[24].

Similarly, a linear association between aquatic insect fecundity and adult female body size has been found, implying that fertility-related parameters influence recruitment and subpopulation competitiveness. Temperature can influence reproduction, egg incubation time, hatching success and length and the onset and termination of diapause. Temperature, photoperiod, water level or floods, interspecies interactions and the availability of adequate spawning sites are all essential stimuli for gonad growth and spawning[25]. Aquatic creatures' metabolic rates are sensitive to changes in water temperature, with a 10°C increase resulting in a doubling of metabolic rate[26].

Most aquatic creatures are poikilothermic and hence unable to modulate their body temperatures, so increased respiration and oxygen demand cause severe stress. Fish and other aquatic species' feeding habits vary greatly with temperature, with the largest feeding rates occurring at moderate temperatures. Some fish species have a temperature threshold beyond which they cease feeding or feed intermittently[25].

Temperature also affects the movements and migrations of aquatic organisms, particularly fish, which are known to use thermal refugia and frequently thermo-regulate by migrating to cooler water when surrounding water temperatures exceed their higher tolerances[8,25]. Water temperature affects aquatic organisms' resistance to parasites and illnesses. For example, increased water temperature promotes schistosome (Bilharzia) transmission by allowing an appropriate snail population to thrive and managing the parasite's incubation period inside the snail[25]. It has been proved that as water temperature rises, fish become more susceptible to infections. Parasite populations also expand rapidly in response to rising water temperatures.

Increased temperature impacts the distribution, growth, reproduction, metabolic rate and other characteristics of aquatic plants. Freshwater has three major algal groups: diatoms, green algae and blue-green algae. These three algal groups have different temperature tolerances. As the temperature rises, the number of diatoms and green algae decreases, leaving blue-green algae as the most numerous. When the amount of primary producers changes, it affects the population of organisms that rely on them for survival. For example, a water flea that can resist a thermal extreme of 35°C will most likely go hungry till death if the diatoms on which it feeds are unable to thrive. Fish feeding on water fleas would struggle to survive, regardless of their capacity to withstand high water temperatures.

Effects of climate change on aquatic ecosystems: Climate change has adversely affected aquatic ecosystems[27-29]. Changes in hydrological patterns, water temperature, oxygen content, ice cover, sea level, ocean circulation, primary production, etc., are pointers to the devastating impacts of climate change on aquatic systems[27]. The melting of snow and ice, temperature fluctuations, precipitation and climatic patterns have all had an impact on the amount, quality and seasonality of water sources. Statistics have shown that, since 1901, precipitation patterns have varied by region; some, especially the northern hemisphere's mid-latitude land areas, appear to have increased precipitation, while precipitation in other areas has decreased[28]. For instance, it was observed that zonal mean precipitation is likely to rise in high latitudes and close to the equator while falling in the subtropics[27,28]. This leads to the modification in flow regimes that impact numerous rivers and wetlands and intensifies the consequences of human water use in developed river basins. Also, the warming of the upper ocean (above 700 m) that we have been seeing since the 1960s has been greatly accelerated by the effects of global warming. Surface waters around the world have increased on average by 0.7°C per century between 1900 and 2016[29]. While ocean temperatures have been rising in many parts of the world during this period, the warming has been most pronounced in the northern hemisphere, especially in the North Atlantic. It is expected that upper ocean warming will continue into the 21st century, especially in the subtropical areas of the tropical and northern hemispheres, while deep water warming will be more intense in the southern ocean. The increase in sea surface temperatures is already beyond natural seasonal variations in subtropics and arctic regions[28,29].

In addition, climate change has a significant impact on dissolved oxygen in aquatic ecosystems and has serious consequences for the global carbon cycle and nitrogen cycle[30]. The average dissolved oxygen in the ocean ranges from super saturated Antarctic seas down to zero in ocean sediments when the oxygen demand exceeds supply over a long period. There are many circulatory systems, including open ocean oxygen minimum zones (OMZ's), coastal upwelling zones, deep basins of semi-enclosed seas, deep fjords and more. However, widespread decreases in oxygen in coastal waters since the 1960s and the expansion of tropical oxygen zones in recent decades have raised concerns. Ocean warming has an impact on the solubility of oxygen in water, which accounts for approximately 15% of the current global oxygen loss and over 50% of the global oxygen loss in the top 1000 m of the ocean due to increased stratification. It is estimated that a further 85% of global ocean oxygen loss is due to reduced circulation.

Furthermore, between 1979 and 2012, the amount of Arctic sea ice was estimated to have reduced at a rate of 3.5-4.1% each decade[6,31] and the average annual extent of Arctic and perennial sea ice has reduced by 11.5±2.1% each decade. Almost all glaciers throughout the world have declined; between 2003 and 2009, glaciers in Alaska, the Canadian Arctic, the Greenland ice sheet's edge, the Southern Andes and the Asian Mountains lost the most ice. Soon, as global mean surface temperature rises, Arctic sea ice cover is projected to reduce and thin more, as well as northern high-latitude springtime snow cover and near surface ice. While sea level rise is a direct outcome of ice melting and is projected to have long-term consequences, the loss of mountain glaciers will have immediate effects on river flow and lake levels before disappearing in the future.

Ocean circulation is one of the ways that climate change affects aquatic systems. Currents carry heat, oxygen, nutrients, biota and freshwater around the world, affecting local climates and ecosystems. These currents are governed by atmospheric circulation patterns, variations in the amount of insolation absorbed with latitude and the water cycle. As the planet warms as a result of rising greenhouse gas concentrations in the atmosphere, these variations will have an impact on regional ecosystems all over the world[32,33]. The meridional overturning circulation (MOC) is primarily responsible for the ocean's ability to transport excess heat from the tropics to middle and high latitudes, as well as its carbon sequestration.

Another significant impact of climate change is ocean acidification, which causes a fall in pH levels. Ocean acidification is caused by the oceans absorbing CO_2 from the atmosphere. The MOC is principally responsible for much of the ocean's ability to transport excess heat from the tropics to middle and high latitudes, as well as its carbon sequestration. Carbonic acid (H_2CO_3) is produced during the process, which is then separated into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The presence of free hydrogen ions decreases the pH of the ocean, which has negative consequences for the ocean environment, such as decreased calcification, metabolic rates, immunological responses and energy for fundamental body processes[1,34]. The principal source of this is human-caused CO_2 emissions, which exceeded 410 ppm in 2020[31]. Between 1950 and 2020, the average pH of ocean surface water declined from about 8.15 to 8.05. As atmospheric CO_2 levels grow, the oceans absorb more of it, resulting in the aforementioned detrimental effects.

Climate change also affects primary production[17,35]. The phytoplankton community, which is critical for primary production, is located at the bottom of the aquatic food chain, controlling the energy and food available to higher tropic levels. Models of global marine productions predict increases[36,37] or losses of up to 20% by 2100[38] due to primary production's ability to incorporate changes in light, temperature and nutrients. According to recent reports on tropical ocean primary output, it is projected that worldwide marine primary production will decrease by 6.3% by 2100[35].

Climatological changes due to climate change have also been shown to impact water quality. Only approximately 0.5% of the world's water has been reported to be usable or available as freshwater. Over the last few years, climate change has had a hazardous influence on that supply, with significant implications for water security. Climate change will also have an impact on water quality, as higher water temperatures and more frequent floods and droughts are expected to exacerbate many forms of pollution[24].

Climate change as a thermal stress multiplier: The intricate interactions and interplay of elements in the aquatic environment dictate the majority of the effects of climate change and thermal pollution. Thermal stress caused by thermal pollution and climate change has far-reaching consequences on biodiversity, community structure, material cycling and other ecological properties in aquatic systems receiving heated effluents[39]. Water temperature reduces CO_2 concentrations, with primary producers in aquatic habitats driving CO_2 dynamics.

Because freshwater communities are often highly size-structured, geographically limited and dominated by ectotherms, whose contributions to ecosystem functioning significantly depend on environmental temperature, they are particularly vulnerable to warming[40]. Numerous phytoplanktonic ectotherms, use primary production to contribute significantly to the sequestration of carbon in freshwater environments. The ratio of heterotrophic to autotrophic plankton, as well as the rates of photosynthesis and community respiration, may shift as a result of climate change[40]. Increased herbivory has the potential to enhance CO_2 emissions into the atmosphere by decreasing phytoplankton biomass. Conversely, warming might be detrimental to zooplankton grazers because their metabolic needs rise more quickly than their rates of grazing; consequently, rising temperatures might negatively affect zooplankton body size and population growth rates, breaking phytoplankton's top-down control. By changing the relative competitiveness of particular phytoplankton species, warming can have an impact on community dynamics[41,42]. Higher temperatures are advantageous to some species, particularly when the environment matches their particular temperature threshold. Other taxa that are pushed away from their temperature optima may go extinct locally or suffer competition from dominating species. This also holds for different phytoplankton species' ability to absorb carbon. Very efficient carbon absorption systems are seen in cyanobacteria[43,44] which increase their internal concentration compared to their external environment.

The increase in greenhouse gases in the earth's atmosphere would produce two key changes in the ocean[38]: (i) A decrease in total carbonate alkalinity as atmospheric CO_2 levels rise. This variable is expected to have a considerable impact on the global ocean's acidity and carbonate ion pool. If carbon dioxide concentrations in the atmosphere are doubled, the aragonite saturation state in the tropics will decrease by 30% by 2050; (ii) Increased sea level will occur as a result of the increase in global temperature, due to the thermal expansion of ocean water, glacier melting and changes in ice sheet distribution. Sea levels will rise by between 9 to 29 cm over the next 40 years, or 28 to 29 cm by 2090[6,45,46]. Changes in global temperatures can have a direct impact on the speeds and directions of ocean water circulation, hence influencing the sea ecosystem. For example, a 1°C increase in temperature over a month can cause coral "bleaching" a process in which the majority of coral symbionts are destroyed, causing the corals to turn white and become fragile[6]. Climate change and rising levels of ultraviolet light provide new challenges for freshwater organisms, compounding already existing constraints.

Rapid land-use change, habitat disruption and climate change are seen as major threats to aquatic ecosystems. A warmer environment increases evaporation from water surfaces and plant transpiration, resulting in distortion of the water cycle. Freshwater fauna faces a variety of problems, including pollution, the introduction of invasive species and habitat loss and degradation. Changes in hydrologic cycle and rising temperatures will have a direct impact on lake ecosystems, rapid climate change has the potential to drive extinction at multiple taxonomic levels and species-level extinction is most likely to occur in highly restricted geographic distributions of fish, where there are regional variations in the proportional occurrence of specialized species[46].

Water eutrophication, which happens when excessive concentrations of nutrients such as nitrogen and phosphorus are present in the water, is expected to spread and intensify under current climate change conditions. Climate change can affect eutrophication both directly and indirectly through interactions between meteorological parameters and nutrient availability[13,32,47,48]. Changing hydrological cycles and atmospheric and meteorological features, such as precipitation patterns, atmospheric water vapor and evaporation, all have an impact on water quality by exacerbating various types of pollution, particularly eutrophication. Warmer temperatures can potentially lead to earlier and longer periods of possible algae blooms[48]. When water temperature and nutrient concentrations rise, algae proliferate, resulting in eutrophication and algal blooms. As phosphorus and nitrogen concentrations rise in lakes, rivers and estuaries, cyanobacteria become increasingly prevalent. Cyanobacteria grow faster when the water temperature goes above 25 °C. Warmer temperatures will also influence nutrient loadings from sediment, affecting the water's trophic status[49]. Higher temperatures lead to a more severe stratification of the water column, which reduces the amount of nutrients available in the surface water. Under these circumstances, nutrients will be accessed by cyanobacteria from lower depths, hastening the discharge of nutrients into the water[41]. In addition, warmer temperatures will hasten microbial activity in the sediments at the bottom of lakes and rivers, accelerating the release of phosphorus internally and greatly increasing the overall nutrient load in the water[34]. Moreover, water's potential for self-purification and degradation coefficients are decreased at higher temperatures[47,49]. Therefore, even in the case of climate change, internal sources of nutrient loadings may still lead to the eutrophication of water, in the absence of external sources of nutrient loadings such as waste discharge and non-point pollution[50].

Addressing thermal pollution and climate impacts in aquatic ecosystems: The 2015 Paris Climate Agreement prioritized effective and progressive solutions to the urgent threat of climate change, including mitigation and adaptation measures, with a special emphasis on ecological system vulnerabilities. Tackling thermal loading will not yield the intended results unless the worldwide problem of climate change is addressed. Here, two key approaches are advocated for addressing the worsening impact of climate change on thermal stress in aquatic ecosystems: (i) Practical measures and (ii) Governance, which includes regulatory and legislative solutions.

Practical approaches: There are several methods for removing heat from cooling water and other industrial effluents. Some of these methods are described here:

- **Wet tower:** The most common way of reducing thermal pollution is to stream water in a thin sheet over baffles in enormous hyperbola-shaped towers, in the expectation that air drafts coming at the base can evaporate the heat. An alternative way is to spray hot water inside the tower in a fine mist, which is subsequently condensed by chilly air rising through the tower, releasing heat that is carried out of the tower by the air column. In both cases, the cooled water is recycled or discharged into the environment
- **Dry tower:** The hot effluent in a dry tower is confined in a network of pipes similar to an automotive radiator. Air passes over the pipes through a wide surface, allowing heat to be exchanged by radiation and convection
- **Cooling ponds:** Cooling ponds are recognized as the most simple and cost-effective method of moderating thermal discharges. It is designed to chill heated water and/or store and distribute cooling water to another facility
- **Artificial lake:** Human-made water systems can give an alternative method of cooling power plants. Discharging heated water from one end and extracting cooler water from the other is beneficial for water cooling. The heat in the water body is eventually discharged into the atmosphere through evaporation

Governance

Regulatory and policy strategies: Environmental regulations could encourage the use of alternative cooling methods[50]. These regulations could require industries to monitor the temperature of their effluent regularly and limit the amount of heated water released into the aquatic environment.

In 1956, the Ohio River Valley Water Sanitation Commission's (ORSANCO) Aquatic Life Advisory Committee developed one of the first temperature requirements[4]. These parameters were designed to preserve a diverse fish population and sustain harvestable crop production in the Ohio River Watershed. The committee suggested that the temperature of incoming water:

- Should not be raised above 34°C at any place or at any time
- Should not be raised above 23°C at any place or at any time during December through April
- Should not be raised in streams suitable for trout propagation

According to the regulation, maximum weekly average temperatures are intended to provide the following benefits: Protection against mortality in cooler months; protection for physiologically optimum temperature in warmer months; protection for successful migration, spawning, egg incubation, fry rearing and other reproductive functions during reproductive seasons; and preservation of normal species diversity.

Immediate implementation of relevant actions: The present level of global GHG emission is putting us on course for a substantially warmer planet than previously forecast. So if emissions should be reduced early enough to avert warming of more than 2°C, we must implement mitigation policies immediately. The amount of GHG emissions projected for the future should concern the entire global society. According to two alternative emissions scenarios, RCP 2.6 (low emissions scenario) and RCP 8.5 (high emissions scenario), global surface temperatures are anticipated to rise by 0.3 -1.7°C and 2.6-4.8°C, respectively, by the end of the twenty-first century[2,3,6]. This suggests that quick action is required to control the rise in global temperatures.

For communities, businesses and ecosystems to be resilient against natural disasters, reduce poverty, switch to green energy and preserve aquatic ecosystems, water security is essential. To ensure the demands of the global community, climate policy must simultaneously implement long-term strategies and promptly address concerns regarding water security.

Cross-border collaboration in adjustment: To prevent maladaptive consequences from a basin perspective, address climate impacts that cross national borders (such as droughts or flooding of transboundary rivers) and maximize the potential co-benefits of improved regional cooperation, such as peace and stability, increased planning space, shared costs and benefits and decreased uncertainty due to data exchange, transboundary cooperation is necessary.

Better finance for climate change: Green and blue climate bonds are good examples of creative, integrated finance solutions for water and climate that can help speed up climate investment across the economy. If the appropriate climate finance is given, water resource management will help to improve sustainable development outcomes by boosting local employment generation and community climate resilience.

Nature-based mitigation measures: Because water is critical to achieving the 2030 sustainable development goals, climate-resilient water management can serve as a tool for coordinating these global frameworks. Recognizing the potential of aquatic systems for climate mitigation and improving aquatic system management is a critical component of effective climate mitigation and adaptation measures, as outlined in the 2015 Paris Agreement.

Nations should start reviewing and implementing their national plans, particularly their Nationally Determined Contributions (NDCs), as required by the Paris Agreement. Aside from carbon sequestration, other valuable direct and indirect co-benefits provided by aquatic ecosystems, such as flood risk management, biodiversity recovery, sustainable community livelihoods and water quality improvement, should be incorporated into nations' NDCs emission reduction targets. This will assist communities, nations and basin authorities make confident, risk-informed decisions that can help improve ecosystem health, build climate resilience and reduce the risk of water-related calamities. Degraded aquatic habitats should be restored and protected to guarantee their ability to operate as GHG sinks[9]. Human activities in aquatic systems should be regulated and monitored to protect the existing natural aquatic ecosystems.

Evaluation of methodological approaches for addressing cumulative effects of thermal stress: It has been established that conventional experimental research concentrated on the incremental effect of temperature and other climate change drivers on a given organism is critical. The number of stressors increases the complexity of the experimental design, logistics and data processing of multiple-stressor research. Notwithstanding these challenges, a multitude of methodologies have been devised for diverse levels of biological organization. These encompass experimental approaches for studies focused on individuals, statistical modeling and trophic-dynamic ecosystem simulation models at the ecosystem level[51]. Several methods have been developed for different levels of biological organization despite these difficulties.

To better understand how each stressor and its combination influences organisms' reactions, laboratory experimental research can evaluate individual and multiple stressors at the same time and target specific endpoints or pathways. To determine the interplay of stressors, performance curves for each driver must be generated, as well as a deeper knowledge of their methods of action. To examine the combined impact of several drivers, multiple scenarios for each targeted category must be tested in addition to evaluating their effects[52].

Although they are restricted to species that can be maintained in lab environments, exploratory investigations can be thought of as a mechanistic approach to multi-stressor testing. Because laboratory research usually focuses on individual or sub-individual responses, another drawback of these investigations is their ecological applicability. Laboratory multifactorial research can oversimplify complex systems, even though they are more ecologically realistic than single-factor studies[24]. Mesocosm studies are also used to look at how different pollutants and stressors interact[14,32]. They can be thought of as a simplification of natural systems, enabling mechanistic testing of one or more drivers at ecologically relevant scales in highly repeatable and controlled environments at ecologically relevant scales.

Numerous types of research have shown that finding synergistic effects of pollution and climate change is a difficult endeavor that typically relies on powerful statistical tools[50,51]. It is also crucial to emphasize that ecosystem-based modeling necessitates extensive multidisciplinary collaboration to ensure that all ecological indicators are reliably gathered and evaluated in complex aquatic ecosystems. Furthermore, determining baseline reference points and thresholds is difficult unless a control location is available outside of the *in situ* investigation's territory. Expert opinion may also be used to clarify model assumptions and evaluate results[24,35]. Nonetheless, it is crucial to remember that ecosystem-based modeling necessitates excellent cross-disciplinary collaboration to ensure that all biological indicators in intricate aquatic ecosystems are precisely collected and evaluated[52,53].

To scale up from physiological responses to large-scale integrated ecosystem responses in future climates, researchers at different levels of the biological organization must collaborate to comprehend and predict the effects of global change on a variety of organisms. Generally speaking, every methodological approach has potentials and limitations that add to the complexity of research meant to assess synergistic effects.

Knowledge gaps: Strong evidence that aquatic resources are susceptible to and could be severely damaged by climate change can be found in both observational data and climate models. Thus, the changing climate will undoubtedly put further strain on aquatic ecosystems that are already under stress from thermal pollution. However, uncertainty at every stage of the assessment process limits the ability to quantify future changes in hydrological variables and their impacts on systems and sectors, making it challenging to develop a comprehensive and holistic understanding and practical solutions for addressing and mitigating heat stress in aquatic ecosystems.

As a result, improved access to data and observational records is critical for improving comprehension of current changes and for a better understanding of model projections, which are required for the adaptive management needed in the face of climate change.

Major gaps in observations of climate change related to thermal stress in aquatic ecosystems should be filled by the following: using published field or laboratory data, such as growth curves and reproduction rates, to estimate parameters, including the parameter that quantifies the dependence of rates of body functions on temperature. Knowledge advancement depends on improved data availability. Scientists may now estimate and obtain species-specific characteristics by using these approaches.

Furthermore, evidence is required to determine the mode of action of various stressors on a certain species at different temperatures. Similarly, understanding the costs and incentives for implementing pollution-reduction measures, as well as techniques for determining the cost of thermal stress, is critical for the development of thermal stress-addressing instruments[46,54]. Knowledge about the most effective methods of education and awareness creation should be created.

Future research needs: Improving the evaluation of the consequences of growing climatic variability on aquatic resources, should be the main goal of future research on thermal stress. Primarily, techniques that enhance the creation of data sets at the local level and basic computerized watershed models linked to climate change, will enable water managers to appraise the effectiveness and resilience of their systems, while assessing impacts in the face of uncertain climate projections. Priority research areas should include identifying and testing locally appropriate biomarkers, modeling the effect of thermal stress on biota, harmonizing data collection and calculating the economic costs of thermal stress across countries and projects and determining how to effectively share relevant knowledge to incentivize desirable practices[43,55].

CONCLUSION

It is becoming more and more clear that we cannot keep adding waste heat to aquatic systems without endangering the environment. If the natural ecosystems are to continue, then this thermal energy has a great deal of promise for creative applications that need to be realized. Aquatic ecosystems around the world have been and will continue to be altered by the combined effects of thermal pollution and climate change. If significant action is not taken, we anticipate that the long-term patterns of change that have been noted in recent decades will not only continue but in many cases get worse soon. More severe effects on aquatic ecosystems than are currently seen will probably come from interactions between climate change and other stresses on aquatic ecosystems that cause unexpected, nonlinear biological responses.

The development of effective management strategies will be further complicated by the nonlinear responses of aquatic ecosystems to climate change. Global aquatic ecosystems will undergo unprecedented and unpredictable changes due to the compounding influence of multiple stressors and currently unanticipated ecosystem responses. Given the numerous problems affecting aquatic ecosystems, research is urgently needed to understand the intricate ways in which aquatic ecosystems respond to thermal loading in the context of climate change.

SIGNIFICANCE STATEMENT

This study synthesizes the literature on the effects of thermal pollution and climate change and their cumulative effects as thermal stressors on aquatic ecosystems, with the view to identifying the solutions, challenges in methodological and study design, research needs and gaps in knowledge. The study revealed that, although authors have demonstrated in-depth knowledge of the impact of thermal stress on aquatic organisms in laboratory conditions, not much data has been put forward to show an adequate understanding of these impacts under natural conditions.

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