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Review

The Effects of Climate Change on Aquatic Ecosystems in Relation to Human Health

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ABSTRACT

This review paper aimed to summarize the climate change impacts on water sources and their relation with human and ecosystem health and evaluate better management strategies. In aquatic environments, climate change causes alteration of biodiversity and species distribution, changes in the duration of biological functions, decreasing productivities, alteration in food web structures, as well as triggering the invasion of various species, and variation in the presence, abundance, and concentrations of various co-stressors. Since the beginning of the 20th century, the surface water temperature in the oceans has risen by about 1°C. Consequently, human well-being is directly and indirectly affected by these alterations. The World Health Organization (WHO) estimates 3.5 million people die from water-related diseases each year. It is projected that the number of water-related diseases will increase due to the effects of climate change. To cope with these problems, alternative water management strategies should be developed to have resilient water systems in terms of both ecological and technological perspectives. Thus, water management requires the cooperation of many sectors including citizens, institutions, public and private sectors, etc. within a multi-stakeholder approach.

Keywords: Climate change, ecosystem services, public health

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INTRODUCTION

"Climate change" defines any alterations in climatic conditions including frequency of extreme weather events (i.e., heat waves, floods, storms), rising atmospheric temperatures and sea levels, melting of ice sheets, etc. caused by both natural events and anthropogenic activities (NASA, 2020). Rising surface temperature is one of the main drivers of climate change and global warming was noted particularly in the late '70s as being attributed mostly to greenhouse gas emissions resulting from industrial and domestic sources (Lipczynska-Kochany, 2018; NASA, 2020; Sun et al., 2020).

Any changes in climate have impacts on the ecosystem, the economy, as well as social welfare including clean air, safe and adequate drinking water, sufficient food, etc. (WHO, 2018a). Climate change is one of the most important drivers for environmental alterations severely affecting biodiversity and ecosystem capacity and functions (Bai et al., 2019). It can result in water temperature rises, acidification, and deoxygenation in aquatic ecosystems. The water temperature rose two-fold more than that in 1993 (Yadav & Gjerde, 2020). The ocean acidity has increased by 30% since preindustrial times and the dissolved oxygen levels have decreased almost 1-2% since the mid-20th century. Furthermore, due to the rising water temperature, the intervals and durations of heatwaves have increased. These changes cause alteration of species and biodiversity, as well as productivities and food web structures in the aquatic environments (Yadav & Gjerde, 2020). The changing environmental conditions will also trigger the invasion of various species and have direct impacts on ecosystem well-being (Figure 1).

Particularly, it is projected that the Mediterranean region will suffer from climate change most which will affect available water quantity and assimilation capacities of the water sources and cause poor water quality (Rocha et al., 2020). Decreasing the water levels may cause poor water quality revealing problems for the ecosystem and public health. The World Health Organisation (WHO) has projected that climate change will cause approximately 250,000 deaths per year in the period 2030-2050 mainly from malnutrition, malaria, diarrhea, and heat stress (WHO, 2018a).

Figure 1. Climate change effects.

Water management requires the cooperation of many sectors including citizens, institutions, public and private sectors, etc. within a multi-stakeholder approach. This paper aimed to address the climate change impacts on water resources and their relation to human and ecosystem health.

The relation between ecosystem services loss and climate change

The ecosystem, which is under threat by the acceleration of the demand for resources and environmental changes, provides many services and products for human well-being directly and/or indirectly. The Millennium Ecosystem Assessment revealed that many of the ecosystem services such as water purification and natural hazard regulation have been under deterioration and the level of disturbance will be in an upward trend in the following years (Bai et al., 2019). Ecosystem functions are directly correlated with biodiversity, and the physicochemical properties of the environment and higher biodiversity are usually attributed to higher rates of ecosystem functions (Heinrichs et al., 2016). There are dynamic interactions between various species and their environments in which specific ecosystem functions are attributed to a specific group of species (Heinrichs et al., 2016). Since global warming is a fact in this century, there is a growing body of research evaluating its effects on biodiversity and its relation to the capacity and function of ecosystems. To understand these interactions, phylogenetic databases should be improved. One of the main drivers for shifts in the functioning of the ecosystem and biodiversity loss is climate change. Any kind of difference in climatic conditions (i.e., temperature, precipitation) results in the transformation of hydrological regimes of freshwater ecosystems (Tsang et al., 2021) and aquatic ecosystems are considered more susceptible to the effects of climate changes compared to terrestrial ecosystems in which the climate change scenarios showed that the biodiversity loss rates are greater in the aquatic environments (Huang et al., 2021). Increasing water temperatures, deoxygenation, and acidification are by far the most significant impacts of climate change. Rising temperature leads to changes in basal metabolic functions, species distribution, and the duration of biological functions (Griffith & Gobler, 2020). Moreover, climate change reveals alterations in the presence, abundance, and concentrations of various co-stressors. The stressors resulting from climate change will also have critical interactions with other factors in water and may have complex synergistic effects on the aquatic ecosystem (Griffith & Gobler, 2020). A greater focus on revealing the link between climate change and the food web can produce critical findings that account for the sustainability of aquatic environments. It affects the whole food web in the ecosystem and the responses vary depending on species, level of the effect, location, etc. Climate change also causes the spreading of new species in uncolonized areas and shifts in their distribution across the world (D'Amen & Azzurro, 2020). The invasion may cause decisive environmental and ecological problems triggering the alterations of ecosystem dynamics and functions, extinction of native and endemic species, reducing populations, etc. (D'Amen & Azzurro, 2020).

The climate change forecasts revealed that the Mediterranean region will be one of the most vulnerable areas to global warming and other extreme environmental conditions caused by climate change. With the other stressors in the area, the effects have already been recognized (Lejeusne et al., 2010). The Mediterranean Sea has the highest number of invasive species worldwide (D'Amen & Azzurro, 2020), and these species mostly originate from the Red Sea (e.g. Lessepsian species) (Lejeusne et al., 2010). The thermo-tolerant exotic organisms have become dominant by the warming in which cold stenothermal local species have rarified, conversely.

Rising temperatures promote the proliferation of harmful algae in excessive amounts in inland water bodies. Examples are provided in Figure 2. It also causes acceleration of both the growth rates and bloom frequency and durations (Gobler et al., 2017). Cyanobacteria blooms and their toxins have emerged as a global concern due to the acceleration of the eutrophication process in freshwater habitats (i.e., lakes and drinking water reservoirs) which then reduce the water quality and finally the use of water (Albay et al., 2005; Cai et al., 2014; Koker et al., 2017). It has been reported that some cyanobacteria species are dominant in the aquatic ecosystems due to their adaptation abilities to various environmental conditions thanks to their functional properties such as phosphorus storage, buoyancy regulation, nitrogen fixation, and akinete formation (resting spores) (Mantzouki et al., 2018). For instance, despite the density barrier of water, potentially toxic species, e.g., *Microcystis aeruginosa* and *Anabaena spiroides*, can migrate 12 m to access light and nutrients (Ganf and Oliver 1982). Thus, the fast migratory ability can provide a competitive advantage to these species over other non-migratory or slow migrating phytoplankton. The temperature was found as one of the main parameters responsible for the continental-scale distribution of different cyanotoxins. Thomas and Litchman (2016) stated that optimum growth temperatures of 12 strains of *Microcystis, Raphidiopsis*, and *Dolichopsermum* are in the range of 27–37°C. It was found that an increase in the water temperature stimulates the dominance of well-adapted toxic strains (Mantzouki et al., 2018).

It is thought that climate change will trigger the increase of toxic cyanobacteria in the coming years and therefore pose a serious threat to human and ecosystem health. Chorus et al.(2021) argued that trophic and climatic changes will affect health risks from cyanobacteria. Cyanotoxins are considered one of the most lethal toxin groups with high risks of health disorders and mortality (Albay et al., 2003). Health risks depend on the quantity and time span by which cyanotoxin concentrations exceed WHO guideline values (1 µg/L Microcystin LR in drinking water) for the respective exposure pathway and time span (Chorus et al., 2021). They also cause taste and odor problems, hypoxia, and fish kills. Furthermore, increasing water temperatures stimulate stratification and thus limit nutrient flows (Griffith & Gobler, 2020).

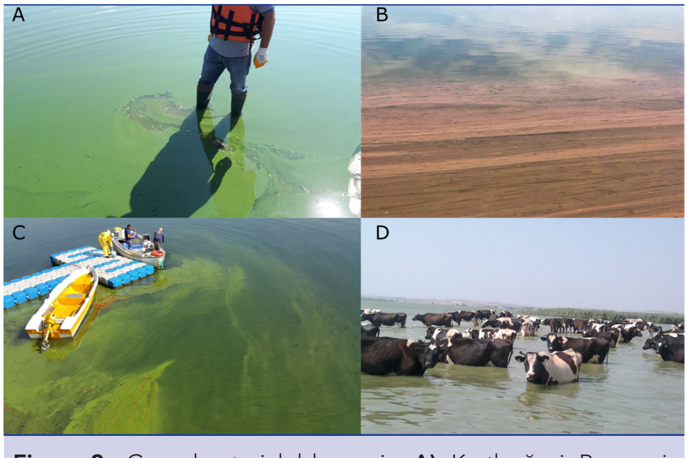

Figure 2. Cyanobacterial bloom in **A)** Kurtboğazi Reservoir (June 2019), **B)** Sapanca Lake (April 2019), **C)** Ömerli Reservoir (October 2015), **D)** Manyas Lake (July 2011).

Fishes are essential for the maintenance of the biogeochemical process and ecosystem functions and climate change causes widespread disturbances to the fish population. They pose different adaptation strategies to combat changing environmental conditions including growth alterations, migration, and mass mortality. Warming of the seawater may also cause an invasion of fish species. An example of invasion within the Mediterranean Sea can be found in the work of Sara et al. (2005) where the authors detected the thermophilic fish species, *Thalassoma pavo*, in the northwest of the Mediterranean Sea. The stresses caused by climate change include rising temperature and the lowering of dissolved oxygen concentrations which mostly result in body size and growth reduction (Huang et al., 2021; Weiskopf et al., 2020). The average body size of fish is projected to fall 14-24% by 2050. Besides, climate change affects the ecological organization in the aquatic ecosystem (Huang et al., 2021). It will detrimentally affect the fish industry in which the quality, quantity, and distribution of the commercial species would decrease (Weiskopf et al., 2020).

Climate changes also affect aquatic plants, especially the invasion of species including formation, distribution, and their impact which then cause an alteration of species interactions, the ecosystem, and human health (Sun et al., 2020). Another group of organisms that also suffer from warming temperatures is corals. The increasing number of heat waves leads to coral bleaching as well as coral cover loss, which also threatens fish communities (Weiskopf et al., 2020; Yadav & Gjerde, 2020). Increasing water temperature also causes bacterial biofilm formation and accelerated decomposition (Lejeusne et al., 2010).

The jellyfish's abundance is dependent on water temperature and salinity. Besides the human-based effects, the higher abundance of jellyfish is attributed to higher salinity levels related to climate change factors. Moreover, some species became abundant due to the higher salinity and temperature conditions (Purcell, 2012). Rising water temperatures have also caused higher asexual production rates in jellyfish (Purcell, 2012).

The relation between public health, water, and climate change

It is now a fact that climate change negatively affects marine and terrestrial biodiversity, and damages ecosystems. As a consequence, human well-being is directly and indirectly affected by these changes (i.e., access to safe water sources, clean air, and sufficient food) (WHO, 2018a).

One of the most important health problems is related to not being able to access safe water sources. The quality and quantity of drinking water are directly and indirectly impacted by climate change, and the use of poor quality water in daily life (i.e., drinking, washing, food preparation, etc.) may cause waterborne diseases (Harper et al., 2020). It is projected that the number of water-related diseases, which are categorized into four groups: water-borne diseases (such as typhoid fever, cholera, etc.), water-based diseases (Schistosomiasis, etc.), water-related vector-borne diseases (malaria, dengue fever, etc.), and water-scarce diseases (scabies, trachoma, etc.), will increase due to the effects of climate change (Hinrichsen, Robey, & Upadhyay, 1997). Diarrheal disease, which is among the water-borne diseases, is a notable public health problem, especially in undeveloped and developing countries. Increasing air and water temperatures, changing rainfall patterns and extreme rainfalls, and seasonal changes affect the transmission of these diseases. Diarrheal diseases peak depending on weather conditions both with droughts and heavy storms (CDC, 2020a). It is estimated that there are 485,000 deaths each year due to diarrheal diseases caused by contaminated drinking water (WHO, 2019). Furthermore, changes in the climatic conditions can result in alteration of the transmission seasons or the geographical area of some infectious diseases (WHO, 2018a). For instance, whereas the water-based disease Schistosomiasis is an endemic disease in some regions of China, it is estimated to expand its impact region and reach 8.1% of China's surface area by 2050 (Zhou et al., 2008).

Malaria and dengue fever, which are among the water-related vector-borne diseases, are highly affected by climatic conditions. Transmitted by Anopheles mosquitoes, malaria kills over 400,000 people every year. These deaths are generally seen in children under 5 years of age in African countries. Studies show that Dengue fever cases will increase as a result of climate change (WHO, 2008). The warming of seawater due to climate change causes the proliferation of some pathogenic bacteria such as *Vibrio parahaemolyticus* and *Vibrio vulnificus*. These bacteria can cause illness through ingestion of raw or undercooked seafood or contact while swimming. On the other hand, the warming in freshwater resources can increase the abundance of *Naegleria fowleri,* which causes primary amebic meningoencephalitis (PAM) disease in humans (CDC, 2020c; USGCRP, 2016).

Temperature increases due to climate change increase drought on a regional and global scale (IPCC, 2014a). It is estimated that by 2030, half of the world's population will be affected by water scarcity and 700 million people will have to migrate for this reason (WHO, 2021a). Water scarcity and drought will adversely affect agricultural, livestock, and fish production, especially in poor regions. It is known that 3.1 million deaths occur each year due to malnutrition and the prevalence of malnutrition will increase due to both decreased food production and poverty in the future (CDC, 2020b; WHO, 2018a, 2021a). On the other hand, studies showed that psychosocial stress and related mental health disorders will be seen in regions affected by water scarcity (WHO, 2021a).

Due to global climate change, glaciers are melting, sea levels are rising, precipitation patterns are changing, and extreme weather events are more frequent and intense. The number of natural disasters caused by weather events has more than tripled since the 1960s (WHO, 2018a). Flood events cause different health consequences. After heavy rains and floods, the contamination of food, drinking water, and recreational water causes water-borne disease outbreaks. Moreover, respiratory system diseases are observed due to mold growth in buildings. Lower respiratory tract infections such as upper respiratory tract symptoms, asthma, pneumonia, and respiratory syncytial virus (RSV) pneumonia occur in those who live in damp residences, schools, and workplaces. Mental health is adversely affected due to the disaster experienced (CDC, 2020a, 2020c, 2020d, 2020e; WHO, 2018a, 2021b). After a flood, vector (such as mosquitoes) breeding areas are formed, and the number of vector-borne diseases increases. Damage to health facilities during floods also negatively affects the provision of healthcare services (WHO, 2018a, 2021b). Additionally, harmful chemicals may be released into the environment during floods, and contact with them may cause toxic effects (CDC, 2018). Considering more than half of the world's population lives 60 km from the sea, rising sea levels will force people to migrate, and this will have various health consequences, not only from infectious diseases but also mental health effects (WHO, 2018a).

Shifting rainfall patterns, floods, and drought will also affect water supply and water management, and sanitation. Sanitation is one of the determinants of health status (WHO, 2018b). Flood, drought, and rising sea levels threaten sanitation systems (e.g., toilets, septic tanks, treatment facilities) (UN, 2020) in which 4.2 billion people today do not have access to safe sanitation. Climate change is expected to worsen health problems related to inadequate sanitation due to the increase in environmental contamination and damage to sanitation systems.

However, within the scope of Sustainable Development Goal No.6, everyone should have sanitation that can withstand climate change by 2030. This forces nations to take precautions and build resilient environments (UN, 2020).

Building Resilient Ecosystems

The influences of climate change vary spatially and temporally due to the variation in susceptibility and adaptive capacity of the affected area (Weiskopf et al., 2020). To determine the level of impact in the short and long term, modeling studies should be conducted to make projections for diversity changes, ecosystem function, and ecosystem services loss, accordingly. With the help of modeling studies, a trend towards ecological responses can be determined. Thus, the necessary precautions and adaptation strategies can be prepared and implemented in the specific region (Morid et al., 2020). It should be valued that a great number of parameters attributed to hydrological and hydraulic characteristics need to be evaluated for these studies. The modeling projects revealed that, besides warming temperatures, heavy storms will occur in some regions and result in poor water qualities due to increasing depositions, particulate materials, and nutrient concentrations. On the other hand, intensification of wind events will directly impact lake thermal stability as well as decrease dissolved oxygen concentrations (Messina et al., 2020).

Resilience can be defined as the ability to overcome and adapt to problems to maintain services for human use considering the natural environment for today and the future (Ofwat, 2015). It is vitally important to maintain diversity, ecosystem functions, and services mainly in relation to sustainability and the constitution of resilience in natural environments (Boltz et al., 2019) as well as human well-being. To make the residential areas resilient to climate change, three main factors namely, temporal variations, spatial heterogeneity, and hydrological connectivity should be sustained. Moreover, the actions should be implemented in the watershed considering stress factors including pollutants, invasive species, etc. (Grantham et al., 2019).

Healthy ecosystems and the continuity of ecosystem services are strongly related to resilience in the watersheds (Dorendahl & Aich, 2021). Resilience contributes to ensuring the maintenance of the functionality of the ecosystem and helps to recover itself in case of any system failures. Building climate resilience includes the cooperation of all stakeholders including governments, private sectors, universities, and civil organizations. It starts with the development of national policies, defining vulnerable locations and problems, involvement of stakeholders, and implementing environment-oriented solutions. Within this concept, ecosystem-based adaptation strategies have a great concern about using nature-based solutions (Dorendahl & Aich, 2021). Reconnection of rivers to the floodplains is one of the green infrastructures that support the re-establishment of its natural course, reducing the risk of erosion and flooding (Brears, 2018). In Singapore, the drainage network was revised by the government and there is a regulation for the private sector which requires the building of detention tanks for stormwater collection to reduce the stress on the public stormwater infrastructures. As another example of green infrastructure, a rooftop park was built in Rotterdam to contribute to flood prevention (Centre for Liveable Cities and Urban Land Institute, 2020). In Tuscon (Arizona, USA), rainwater, which is used for irrigation purposes, is harvested commercially (EPA, 2014).

CONCLUSION

After the 2000s, many countries especially the United Nations and the European Union initiated very detailed research and published reports to minimize the impact of climate change on water resources. Undoubtedly, the measures taken and the studies carried out are quite inadequate. If more effective and sustainable measures are not put into practice, the Mediterranean ecosystem, which is the most affected area by climate change, and the inland water resources of the countries in the Mediterranean belt will experience greater problems.

Since climate change has serious pressures on aquatic ecosystems, alternative solutions should be developed to meet human and ecosystem needs. For this purpose, engineers and ecologists have been working on more efficient, flexible, modular infrastructures and strategies. Thus, green infrastructures come into prominence and are supported by the national governments (Grantham et al., 2019) in which nature serves to have more resilient water systems in terms of both ecological and technological perspectives. An integrated approach including all stakeholders from policymakers to the citizens should be applied for the better management of water resources.

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