Living Lakes
European Association

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Flashlight Study

Lakes and Climate Change in Europe:

Current situation and need for restoration

Compendium of currently available research on climate change impacts and resulting changes in temperatures on lakes and wetlands in Europe, incorporating findings of different countries.

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Impressum

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Cover picture:
The Zicksee, a steppe lake in Eastern Austria, in 2018. Today, in 2023, the lake has entirely dried out.
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Preface

Prof. Dr. Manfred Niekisch
Vice-president of Global Nature Fund

Horrible fires are threatening and destroying forests, wildlife, human settlements and human lifes all over the world. They are the consequence of climate change. Increased temperatures, dry soils, lack of rain are driving these catastrophes. On the other hand, unusual, devastating floods are happening more often than ever before. Hence, from any point of view, water management is the great challenge and an absolute must in our times.

Unfortunately, for too much time waterbodies and wetlands were used in a consumptive, unsustainable way and are not in good shape. This development must be turned around and ended, recognising and respecting the importance of rivers, lakes, peatlands and other eco-systems depending on water.

At the basis of any activity to restore them must stand an analysis of the current situation and convincing arguments for the need for restoration. But restoration involves activities and costs which not all citizens of Europe will recognize in their importance and easily accept. Also, industry, politicians and public authorities have to be convinced of the urgent need to better manage our waterbodies. And all of them must understand the links between climate change and lakes and wetlands. The priorities to fight climate change and properly manage our waters need higher public acceptance. Only then we will be successful in establishing sustainable systems and uses for our earth and its ecosystems all over. It is of direct benefit to the wellbeing of ourselves.

This Flashlight Study on "Lakes and Climate Change in Europe: Current situation and need for restoration" provides an overview over the state of these waterbodies in European countries, documents the need for restoration and from there shows a way forward.

The negative effects of global warming on lakes and other wetlands and vice-versa, the potential of lake and wetland restoration as a cost-effective means for climate change mitigation are well documented in this study.

I do hope that this convincing study will find many readers and a wide distribution and, from there, will lead to appropriate action.

Summary

Climate change is a major driver for the degradation and loss of freshwater ecosystems. Half of the world's lakes are currently experiencing significant water loss, which is exacerbating water scarcity for agriculture, hydropower and human consumption, but also affects a large number of plant and animal species that depend on these ecosystems. At the same time, some regions are facing extreme precipitation events with the potential of severe flooding and degradation of water quality. Both the biodiversity and the ecosystem services that lakes and other wetlands provide are increasingly at risk due to climate change, a trend that can be observed in several areas across Europe.

This study on "Lakes and Climate Change in Europe" highlights present research on the impacts of climate change on lakes and wetlands from different European regions as well as possible mitigation and adaptation approaches and successful project examples. The study also summarizes funding options for wetland restoration and climate change mitigation projects.

Summer temperatures of European lakes have been increasing on average between 0,29 and 0,38°C per decade, a tendency that is clearly dependent on effects of weather patterns. Over the long term, this causes a decrease on ice cover in lakes, leading to a disruption of ecosystem functions during ice-free winters and a transition of lakes from a dimictic to a monomictic state. If greenhouse gas emissions remain at current levels, ice cover in many lakes will permanently disappear by the end of the century. (cf. Dokulil, Chapter 2.1.). Changes in weather conditions and precipitation also affect community composition, algal biomass, food web dynamics and gas emissions. The expected wetter conditions for the coming years, combined with other environmental changes, will most likely result in more turbid lakes and a climate-induced eutrophication due to terrestrial inputs of dissolved organic matter. Climate change, combined with the increasing turbidity and more nutrients in the water, will alter the function and composition of aquatic food webs, indirectly affecting lake ecosystems through landscape changes as well (cf. Bär Lamas, Chapter 2.2.).

These trends are being observed at lakes and wetlands in several European regions, including lake-rich countries in Northern Europe. In Finland, the increase of spring temperatures has affected the composition of the biological communities found in lakes across Lapland. Increasing water temperatures are expected to be problematic especially for cold-water species in small water bodies, and for long-living species with more difficulties to adapt to these changes. The combined effect of climate change and acidification, eutrophication, changes in land use and the impact of alien species may have unpredictable consequences on aquatic species (cf. Chapter 3.7.). In North Norwegian Lakes, salmonid species adapted to cold waters are particularly vulnerable to climate warming as they experience unfavorably high temperatures in the southernmost reaches of their distribution (cf. Chapter 3.8.). At lake Peipsi and lake Võrtsjärv, the largest lakes in Estonia, the continuously increasing water temperatures and eutrophication has led to more frequent cyanobacteria blooms and fish kills. More stringent measures are needed to further limit nutrient loads to lakes through improved wastewater treatment and increased efficiency of fertilizer application (cf. Nõges & Nõges, Chapter 3.2.).

The situation in lakes of Central Europe is similar. In Germany, many regions will be affected by heat, drought or heavy rain if strong climate change trends continue. The west and south of Germany would experience the strongest effects, and rivers and river valleys could be affected by consequences of water-specific risks such as low and high water. Under strong climate change, Germany would become a hotspot for climate change risks (cf. Chapter 3.3.). Changes in rainfall patterns also affect lakes and wetlands and depending on the timing of fertilizer application in surrounding areas, can be of decisive importance for algal development, as has been observed during the monitoring of lakes in the state of Schleswig Holstein (Reck-Mieth, Chapter 4.3.). Extreme climatic values have consequences for water management as well, such as in the case of Lake Balaton in Hungary. The lake has experienced extreme volume changes in recent decades, which threatens the water supply and recreational use of the lake (cf. Kravinszkaja & Szeiman, Chapter 3.5.). In Czech Republic, Lake Lipno is one of the largest water reservoirs of the country and famous for its long history of pikeperch fishery. However, the population of this and other cold-water fish species typical of Central Europe are at risk of collapsing due to temperature changes as well as other factors such as invasive species, eutrophication and overfishing.

Southern European countries could face even stronger consequences under severe climate change, including a significant decrease in water availability (cf. Chapter 3.1.). Mediterranean wetlands and saline lakes in Spain have an enormous potential for carbon sequestration, but they have been greatly impacted by changes in land use and pollution, water eutrophication, morphological and hydrological alterations, and the effects of climate change. Particularly increasing temperatures and hydromorphological alterations in these ecosystems may convert them into emitters of methane and other GHG gasses (cf. 3.6.).

Aside from affecting biological variables, communities of organisms, ecosystem functions and landscapes, climate change can influence commercial activities and the availability of water resources. Climate projections reveal a typically North-South pattern across Europe for water availability, with regions in the south of Europe facing increasing water scarcity. A considerable number of people and economic activities are projected to be exposed to the consequences of water scarcity caused by global warming (cf. Chapter 3.1.). Climate change also represents a threat for sustainable growth in aquaculture and fisheries worldwide, and several freshwater fish species will experience suboptimal temperature conditions as temperatures increase. This can lead to a decrease in growth performance and biomass and even a complete loss of cold-water species (cf. Chapter 3.8.).

A number of adaptation and mitigation mechanisms is needed to tackle the impacts of climate change on freshwater ecosystems. Wetlands, particularly coastal wetlands and peatlands, play a complex role in regulating atmospheric GHG concentrations, thus their protection and restoration is of extreme importance and can be a cost-effective and efficient approach to generate a climate cooling effect (cf. Taillardat, Chapter 2.3.). For the protection of peatlands, paludiculture has already been successfully tested and promoted for several years as an approach to action. By establishing peat-forming vegetation, the carbon storage of organic soils can be restored. The rewetting of peatlands will then simultaneously reduce the immense nutrient discharge that can be observed in drained peatlands (cf. Bender, Wichtmann & Abel, Chapter 2.4.). Transformative adaptations to mitigate damage to lakes and wetlands should also focus on progressing into alternative, nature-friendly forms of land use and increasing the size of water-bound habitats (cf. Chapter 3.3.). Strategies should also target irrigation practices to lower pressures on water resources by increasing irrigation efficiency, and shifting from conventional to renewable energy production to reduce cooling water demand and net water consumption (cf. Chapter 3.1.). Regular monitoring of the biological characteristics of lakes and wetlands are also a necessary base for moving toward a knowledge-based management of their biodiversity and resources, as well as a stronger regulation of their use (cf. Chapter 3.8.).

1. Introduction

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This "Flashlight Study: Lakes and Climate Change in Europe" is a compilation of current publications and studies on the impacts of climate change on freshwater ecosystems in Europe. It is obvious that the warming of the climate will increasingly have negative impacts on our terrestrial and marine water cycles. Therefore, it is important to assess the effects of climate change on water bodies in order to understand how to minimise potential negative impacts, develop appropriate adaptation strategies and safeguard our valuable water bodies and their essential ecosystem services.

Warmer air can absorb more water vapour, with consequences for the amounts and probabilities of precipitation. To what extent altered precipitation patterns - in view on amounts and distribution – will affect lakes is not yet fully clear. There is evidence that the number of extreme precipitation incidents is increasing. We can also determine an earlier start of snowmelt at higher elevations in northern latitudes and a decrease in floodplains. All those effects will lead to a higher probability of flooding events. For southern Germany, for example, the project „KLIWA - Climate Change and Consequences for Water Management" (KLIWA working group, Bremicker et al. 2019, 2021) states that although the annual precipitation amounts in most areas of southern Germany have remained roughly constant over the period studied, the seasonal precipitation distribution has changed. KLIWA shows, that winters became measurably more humid with higher risks of winter flooding, while the summers, although somewhat more inconsistent in behaviour, have tended to become drier.

Despite the high complexity of causalities, certain conclusions for the ecology of lakes can be drawn from current observations, e.g. with regard to stratification, oxygen content, nutrient availability or biodiversity. Already about two decades ago, several international studies on lakes provided evidence on climate change impacts on structure and function of aquatic ecosystems (e.g. Schindler et al. 1996; Magnuson et al. 2000; Verburg et al. 2003) and the consequences for ecosystem services of the water bodies (O'Reilly et al. 2003) and substantiated recognisable climate-induced impacts on lakes. For example, climate-induced fluctuations in water levels have been observed on a significant scale in North America (Williamson et al. 2009). Observed changes in water temperatures or in the timing of formation and thawing of ice layers on lakes can also be attributed to climate warming (e.g. Magnuson et al. 2000).

Other lake-specific indicators, such as dissolved organic carbon (DOC) or plankton compositions, are more complex and difficult to assess, but also point to negative impacts on ecosystem services (Adrian et al. 2009). According to Adrian, lake ecosystems are well suited as early warning systems for climate change because, firstly, they are clearly defined and can be studied well; secondly, lakes respond directly to climate change; thirdly, effects of climate-induced changes in the catchment can be taken into account; fourthly, lakes sum up effects over longer periods of time and thus compensate for random deviations; and fifthly, lakes are geographically well distributed and can thus capture different aspects of climate change.

This publication aims to show the important contributions that lakes and wetlands make to society as well as economy, a value that has not yet been sufficiently appreciated. Terrestrial aquatic ecosystems and their riparian areas provide a variety of valuable ecosystem services such as drinking water, food fish, irrigation for agriculture, navigation facilities, flood protection, recreational and tourism benefits. In addition to these services, lake regions often show a very high biodiversity and often have a positive impact on the microclimate. For example, special crops such as vegetables and wine are more likely to grow in lake regions due to positive microclimatic effects. Lakes are also important cultural assets and have spiritual and aesthetic significance. Many of these services have the character of public ubiquitous goods. For this reason, they are frequently used without incurring any costs.

This flash study aims to raise awareness for the value and importance of water bodies and their ecosystem services by illustrating what risks and disadvantages climate change may pose to water bodies and their various user groups. It is intended to increase commitment and responsibility for the protection and conservation of aquatic ecosystems and to create incentives to integrate the impacts of climate change on aquatic ecosystems more strongly into decision-making and planning, to undertake meaningful adaptation measures and to develop new strategies and funding instruments for their protection.

In the Paris Agreement (UNFCCC, COP 21, 2015), 195 countries agreed that man-made warming of the air temperature must not exceed two degrees Celsius compared to pre-industrial levels in order to avoid unforeseeable risks for us humans. Unfortunately, no limit value was set for water bodies in Paris. Efficient measures and adequate regulatory frame-works for the protection and restoration of water bodies and wetlands must be implemented quickly in order to avert massive, climate-induced damage to aquatic ecosystems. This paper aims to make a contribution in this regard.

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2. Climate change effects and mitigation potential of lakes and wetlands

2.1 Effects of global warming on lakes: Past, present and future aspects

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Summary

Based on an admittedly subjective selection from the enormous literature on the subject and own work, an attempt is made to trace the development and impact of global warming on lakes since the 1980s in as many facets as possible. Subsequently, the current status and the aspects that begin to emerge in the near future are explained. Finally, a summary with a personal touch follows.

Preamble

Judging by the number of publications, the scientific study of climate change already has a long history, going back to the first half of the 19th century. However, it rapidly gained importance only in the years after 1950 (Stanhill 2001). Very early on, standing waters or their sedimentary deposits provided essential information for the elucidation of past climate changes (Schmidt et al. 2004). Then, starting around the mid-1950s, there was an increasing interest in climate impact on lakes and other water reservoirs (Ho and Goethals 2020). Deng et al. (2017) noted a turning point toward more climate-focused limnological research beginning around 1991.

The early transition of paleolimnology to questions of climate evolution was probably inherent, as analyses of past environmental change have always been a priority in this field. It is also certainly no coincidence that the increased research activity began shortly after the regime change in climate (Reid et al. 2016), which was also observed in lakes (Woolway et al. 2017).

Introduction

There has been scientific consensus for a long time about global climate change and humanity‘s influence (IPCC 2014). The effects of climate warming are already evident and considered one of the greatest threats to the Earth‘s ecosystems. The first evidence of impacts on ecosystem structure and function came from studies of lakes (Magnuson et al. 1990; Schindler et al. 1996), which showed that lakes are sensitive to changing environmental conditions and thus can be used as early warning systems. Lakes respond directly to immediate weather effects as a result of climate, but also indirectly to processes in the watershed (Dokulil and Teubner 2003). Thus, climate manifests itself through local weather patterns, which affect lakes and cause adapted responses as a result of external and internal factors (Livingstone et al. 2010). In the following, the results achieved so far over the past 40 years are described, the current state of knowledge is outlined, and an outlook is given on possible development in the near future.

Data basis

From the abundance of relevant publications, suited examples were selected in each case, using own investigations or publications with participation of the author.

Results

Climate warming has a direct impact on the physicochemical processes in lakes, which are therefore well researched. An inventory for Austria can be found in Dokulil et al. (1993) and Nachtnebel et al. (2014) and for Europe in Eisenreich et al. (2005). An empirical relationship of air temperature to lake temperature was soon corroborated. For example, Robertson and Ragotzkie (1990) found a 0.5 to 1.0°C increase in epilimnion temperature for every 1.0°C increase in air temperature both empirically and using a dynamic model. Subsequently, additional models were developed and refined, but eventually resulted in satellite air/water temperature detection models (Sharma et al. 2015). Evaluations of annual and seasonal trends in long-term data from numerous lakes yielded varying changes in surface temperature or in vertical profiles, and fairly uniformly a strong increase in water temperature beginning in the 1980s (Dokulil 2000, 2013, 2014a,b,c; Peeters et al. 2002; Persson et al. 2005). Summer temperatures of European lakes have been increasing on average between 0.29 and 0.38°C per decade. Globally, increases of up to +1.3°C per decade have been observed, but cooling rates as low as -0.7°C have also been observed in some lakes (O'Reilly et al. 2015). Similar but much smaller increases (0.1 - 0.2°C per decade) were also observed in the deep waters of numerous lakes (Dokulil et al. 2006a,b). Both trends were clearly dependent on remote effects of certain weather patterns. Climate indices, such as the North Atlantic Oscillation (NAO), affect water temperatures primarily in winter and early spring (Livingstone and Dokulil 2001; Dokulil et al. 2006a,b).

Over the long term, there has also been a decrease in ice cover on lakes (Dokulil et al. 2014; Kainz et al. 2017). Observations of 513 northern hemisphere lakes (Sharma et al. 2019) revealed substantial disruption of ecosystem functions during ice-free winters. With the removal of winter ice cover, dimictic lakes have transitioned to monomictic states (Ficker et al. 2017). At the same time, summer temperature stratification begins earlier in the year and ends later. Thus, the stagnation period during the summer lasts much longer, possibly leading to oxygen deficits in deep water (Luger et al. 2021; Woolway et al. 2021). The vast majority of publications on lake temperature uses averages over the year, seasons, months, or specific periods of the year (O'Reilly et al. 2015). However, trends in minimum and maximum temperatures have now been published and consistently show substantial increases (Ptak et al. 2019; Woolway et al. 2019; Dokulil et al. 2021). The increasing temperature in winter (+0.35°C per decade on average) extends the growing season, affects stenothermic species, and food webs. Maximum temperatures increase by +0.58°C per decade on average. Temperatures of 20°C, for example, are increasingly exceeded for longer periods of time, which potentially affects numerous organisms.

A comprehensive overview of the results of the EU project CLIME (2003-2006) and the years before in Europe is provided by George (2010). The combined effect of restoration and climate warming on the zooplankton of an urban water body can be found in Teubner, Großschartner, and Teubner (2018). A comprehensive overview of the advance of alien zooplankton species based on extensive research and possible future developments is provided by Dexter and Bollens (2020).

The importance of the greenhouse gases CO_2 and CH_4 and the increase in their concentrations in the atmosphere has long been recognized and repeatedly documented (Ciais et al. 2013). Until not too long ago, however, inland waters were not part of the carbon budget. Cole et al. (2007) were the first to identify that inland waters were significant to the global carbon budget, and Tranvik et al. (2009) showed that about 48.3% of carbon is released to the atmosphere as CO_2, while 20.7% stays permanently in sediment. The remaining 31% is discharged to the ocean by rivers and groundwater. Global CH_4 emissions were determined by Bastviken et al. (2011) to total 72.2%, with the remaining 27.8% staying in the system. Recently, Pighini et al. (2018) demonstrated that alpine lakes are emitters of greenhouse gases. Dissolved CO_2 and CH_4 were detected at mean concentrations of 1.10 ± 1.30 and 36.23 ± 31.15 μmol L-1, respectively, in 40 lakes at elevations between 200 and 1,500 meters above sea level. There was no dependence on altitude. The authors conclude from their results that alpine lakes can act as a source of greenhouse gases.

With rising temperatures, an increase in the frequency and intensity of extreme weather events has been observed as a result of anthropogenic climate change (Stott 2016). An example is provided by the early summer of 2018, in which the extreme weather was caused by meanders in the high-altitude strong winds (jet stream) of the Northern Hemisphere (Kornhuber et al. 2019). The same pattern also caused the heat waves of 2003, 2006, and 2015.

How locally different extreme weather events can affect lakes can be illustrated for the two Austrian lake regions in the early summer of 2018. The summer of 2018 was meteorologically classified as the warmest and driest in measurement history, although with regional differences. The drought north of the main Alpine ridge, which began in April, resulted in record lake level declines, as Fig. 1A illustrates. The highest level decline of -68 cm from the long-term mean was observed at Wallersee, the lowest (-7 cm) in two inner Alpine lakes. On the other hand, the lakes of Carinthia, south of the Alps, were hardly affected at all. In lake Mondsee, the water level was -37 cm in June (bottom right image in Fig. 1B), but continued to strengthen through December, as shown in the graph of maximum and minimum monthly levels. Looking at the trend over the period of 1976 to 2020, it is clear that floods occur much more frequently than dry periods with low water levels. Floods with more than 1 m above normal (150 cm) occurred in 1987, 1991 and 2013 (top right image in Fig. 1B).

The effects of extreme storm events on phytoplankton were summarized by Stockwell et al. (2020) based on data from 26 studies. The analysis first identifies what can be defined as „extreme," includes effects of storms and rain and the combination of both on nearly all relevant limnological variables, and describes how different phytoplankton communities respond to storms. The authors conclude that the influence of storm events on lake conditions is not a singular function of storm intensity at a given time and place. A better understanding of the impacts of storms requires a watershed-inclusive approach that considers storm-lake-watershed relationships, as well as the antecedents and time scale of the meteorological impulse, ecological response, and data collection. For alpine lakes, Perga et al. (2018) have already demonstrated that pre-event weather conditions are more important than storm intensity. Using high-frequency measurement data from 18 lakes in 11 countries from all continents, Doubek et al. (2021) showed that temperature changes after storms were mostly smaller than 2°C. In contrast, the range of temperature change from day to day was much larger. Because of the small effect of storms on water temperature, the authors therefore gave preference to changes in nutrient concentration and/or light as effects on biological communities. Experimental increases in temperature reduced phytoplankton diversity. Heavy precipitation, on the other hand, maintained diversity despite changes in nutrient ratios, decreases in temperature, and light (Bergkemper et al. 2018).

Global warming and the associated extreme weather events will also increasingly lead to renewed nutrient inputs, i.e. to climate-induced eutrophication of lakes. The causes are increased discharges from the catchment areas as a result of heavy rainfall and flooding (Dokulil and Teubner 2011; Dokulil 2014c). First signs of deterioration in the hypolimnion were described by Luger et al. (2021).

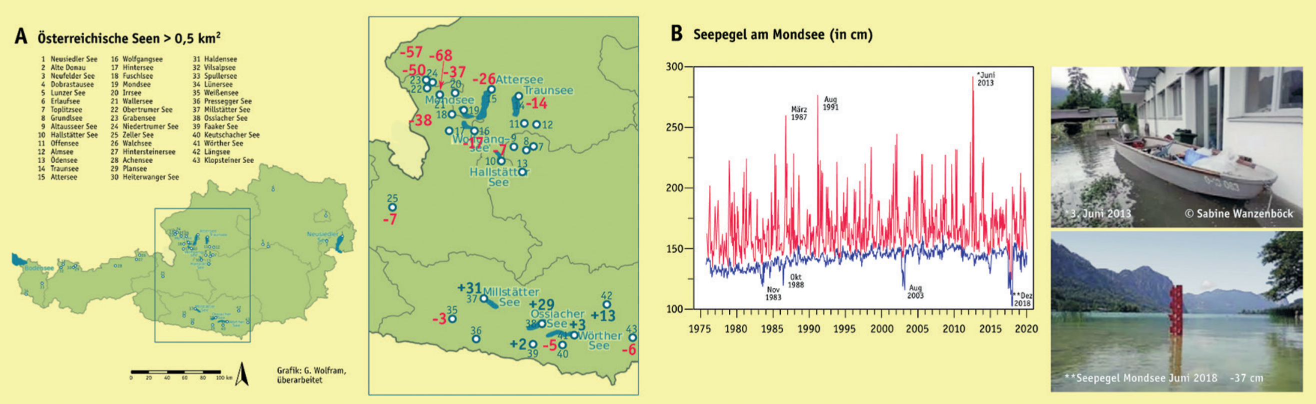

Fig. 1: Extreme weather situations – A. Austria with the two lake regions (left) and the water level of some lakes (right). B. Maximum and minimum monthly water level at Mondsee from 1976 to 2020 (left) as well as floods in 2013 and water level in 2018 as pictures (right), processed. Further explanations in the text.

From the beginning, the focus was also on the effects on the biology of organism communities (Magnuson et al. 1990; Schindler et al. 1996; Hobbie et al. 1999). Countless publications were subsequently devoted to different species, groups of organisms, and biotic communities. Dokulil and Teubner (2012), by analyzing 40 years of data, demonstrated that the depth location of a population of *Plaktothrix rubescens* in the metalimnion depends significantly on climate signals and environmental conditions in the water column. Climate warming favors the taxon, especially in the spring. Longer periods of stratification have little effect on biovolume development. The effect of the 2015 heat wave on phytoplankton primarily affected *Plaktothrix rubescens* which shifted its center of gravity from 11 to 16 meters (Bergkemper and Weisse 2017). Zohary, Flaim, and Sommer (2020) analyzed the effect of increasing water temperature on phytoplankton size. Global warming causes individual species or colonies to become smaller, but at the same time shifts the community toward smaller forms. Work on the effect of temperature on morphologically defined functional plankton groups found different effects of increased temperature (Segura, Sarthou and Kruk 2018). All groups responded positively, with some experiencing a decrease in growth rate with increasing temperature, and others experiencing a rapid decrease in growth rate after exceeding a threshold temperature.

The changes in zooplankton population dynamics due to direct and indirect effects of elevated temperature are explained by Wojtal-Frankiewicz (2012) using Daphnia populations as an example. Even small warmings during a short but critical phase can lead to destabilizations in the food web by uncoupling trophic relationships.

Fish fulfill a key role in the dynamics of lakes. With an increase in temperature, there are changes in the composition of the fish fauna. Altered feeding behavior leads to greater feeding pressure on zooplankton and macroinvertebrates, which is essentially similar to the effects caused by eutrophication. Warming may thus result in the need for lower nutrient concentrations to ensure good water quality (Jeppesen et al. (2010, 2012)). To understand the complex relationships among organisms and the interactions with climate warming, Woodward et al. (2010) analyzed the effects of a wide range of stressors at different temporal-spatial levels, which required models, experiments, and observational data from entire ecosystems. From a study of 54 food webs of Canadian lakes using stable isotopes, Tunney et al. (2014) concluded, among other things, that cold-loving organisms change their behavior to stay in the cool range when their habitats warm. Other authors, such as Hansen et al. (2017), predict changes in fish community composition as stream temperature increases. Experimentally, Murphy, Romanuk, and Worm (2020) showed that warming causes more direct effects on organisms at the base and top of the food web, respectively, than on trophic groups in between.

The complex interactions between cyanobacteria, zooplankton, ciliates, bacteria, viruses, and fungi in the course of climate warming were summarized by Wilk-Wožniak (2019) in a review article, resulting in an even more complicated network of relationships than originally thought. It appears that mass unfolding of cyanobacteria are not the end point of an evolution, but rather just a state in a sequence.

Current status

Environmental variables, phytoplankton, and cyanotoxins were surveyed in an extensive study of 369 European lakes (Mantzouki et al. 2018). One of the key findings was the complex interplay of regional climate, local factors such as nutrient elements and morphometrics, and biological variables (e.g., species composition) for the development of cyanobacterial algal blooms. Modeling of the spring maximum phytoplankton bloom in western Europe using meteorological data from 1,962 monitoring sites spanning 31 years showed a strong dependence on the timing of ice breakup and the onset of stable thermal stratification (Gronchi et al. 2020).

Measurements by the U.S. National Oceanic and Atmospheric Administration (NOAA) (NOAA 2021) found that July 2021 was the warmest July since 1880, averaging +0.93°C above the 20th century mean of 15.8°C over land and ocean. It surpassed the Julys of 2016, 2019, and 2020, and in Europe it was the second warmest July ever recorded. It was also particularly warm in Asia, where it exceeded the 2020 high. This means that 10 of the warmest July months have occurred in the period since 2005.

Accordingly, 2021 was affected by climate change to a high degree. The ‚World Meteorological Organization', for example, first headlined Summer of extremes: floods, heat and fire (https://public.wmo.int/en/media/news/summer-of-extremes-floods-heatand-fire) in its July news and then identified water-related risks as the main disasters of the past 50 years (https://public.wmo.int/en/media/pressrelease/water-re-lated-hazards-dominate-disasters-past-50-years).

Outlook

For at least half of the world's lakes, winter ice cover is ecologically important to minimize evaporation rates, moderate summer water temperatures, and contain algal blooms. At the same time, lakes provide recreation, transportation, and food for millions of people. According to a projection by Sharma et al. (2021), ice cover in many lakes will permanently disappear by the end of the century if greenhouse gas emissions remain at current levels.

According to the latest climate report (AR6) by the IPCC (2021), the current temperature at the Earth's surface has increased by 1.1°C, relative to the 1850-1900 average, and if global greenhouse gas emissions continue at current levels, global temperatures are projected to increase between 2.1 and 3.5°C by 2100. To reach the Paris climate target after all, for example, the time span has already become very short.

Particularly high temperature increases of up to 5°C are predicted for cities, which would more than double the 1.5-degree limit. The range of uncertainty in the AR6 forecasts has decreased significantly and now ranges from 2.5 to 4°C.

In many regions, but especially in the Mediterranean, an increase in the number of days with temperatures above 35°C is very likely. Associated with this, an increase in droughts, fire danger, floods and generally an increase in extreme weather periods by 2050 can be assumed with high probability. As one of the many possible consequences for lakes, recent climate warming-induced eutrophication and its impact must also be considered, as mentioned earlier (Dokulil and Teubner 2011; Dokulil et al. 2014).

Impacts on inland waters will ultimately entail changes in the oceans, however, because in addition to sea rise, ocean acidification, and a potential risk of emissions of nitrous oxide (N2O), a slowdown of the Gulf Stream in particular could have major negative impacts on the climate not only in Europe but worldwide.

Summary

Since at least the mid-1980s, there has been a significant, rapid increase in global temperatures, driven in large part by anthropogenic emissions of greenhouse gases, even if some still refuse to admit it. Increasingly extreme weather events, especially in 2021, have made clear what is likely to be in store for us in the future. These developments also directly or indirectly affect water bodies and water resources as a whole.

If one follows the detailed report of the IPCC (2021), there is still time to act and thus mitigate the most dramatic effects of the climate crisis. However, the question is how the global population and, more importantly, global policy makers will respond to this challenge. The problem, like many other environmental problems, can only be solved globally through cooperation of all states. It is possible that humanity will have to undergo a rigorous systemic and economic transformation, but this seems to be out of reach at the moment. The minimum requirement is to switch to clean energy sources and a drastic reduction of greenhouse gas emissions, in order to at least limit the further temperature rise. One essential question is hardly discussed and is virtually unsolvable, namely the constant increase in the world's population, without which many other environmental problems other aside from climate change would not exist.

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2.2 Meteorological parameters of climate change: Air and water temperature, ice cover, evaporation and interaction with biological factors

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The global impacts of climate change on lakes have been investigated in a large number of studies over the past two decades (Schindler 1997; Livingstone 2003; Williamson et al. 2009; Niedda et al. 2014; Ito and Momii 2015). Some of the most widespread and already detectable physical impacts of climate change on lakes include warming of surface water, shorter periods of ice cover, and changes in evaporation, water balance and mixing regimes. These factors are connected through various mutually reinforcing or mitigating interactions, which limits the predictability of specific responses of lakes to climate change. For example, changes in ice cover and water temperature affect evaporation rates, but are in turn also influenced by them.

If precipitation conditions remain unchanged, reduced ice cover, increased temperatures and increased evaporation rates of lakes will lead to a decrease of the water level along with a reduction of lake surface area. The surface runoff and direct precipitation into the lake, however, are also subject to climatic variability in the watershed and can amplify or even overlay the effects of evaporation on water level or lake extension (Woolway et al. 2020). These complex interactions need to be taken into account when discussing individual variables to understand the effects on the delicate balance of aquatic ecosystems. Despite the high degree of complexity, some of the relevant factors are discussed and evaluated separately in the following.

Water temperature

Water temperature is an important parameter of aquatic ecosystems that strongly influences the metabolic rate of organisms and the activity of bacteria and algae. A change in water temperature can affect the balance and species composition of an aquatic ecosystem and alter the trophic status. Dynamic processes in lakes, such as thermal stratification and mixing dynamics, are also closely linked to water temperature. The energy balance of large lakes is dominated by heat exchange processes at the surface (Lieberherr & Wunderle 2018).

A recent paper on global lake responses to climate change by Woolway et al. (2020), published in Nature Reviews Earth & Environment, indicates that lake surface water temperature (LSWT) is a good indicator of climate change because it is influenced by climatic and lake-specific characteristics that contribute to the energy balance at the lake surface. Key factors include the amount of incoming shortwave and longwave radiation and the fraction of solar radiation absorbed at the lake surface (albedo); as well as the advection and storage of heat in the lake and the heat loss at the air-water interface due to outgoing longwave radiation and turbulent heat fluxes. These factors are influenced by many climatic variables, such as cloud cover, wind speed over the lake, humidity, and air temperature, but especially by two critical lake surface parameters: LSWT and ice cover. Therefore, changes in any of these climate variables can affect LSWT and ice cover through multiple feedbacks in the surface energy balance (Woolway et al. 2020).

In summary, the lake surface water temperature (LSWT) determines the energy and mass exchange between water and the troposphere. It is also an important parameter in meteorology and local climate models. LSWT can be considered an important indicator of regional climate change. Several recent publications have analyzed climate signals in lakes by examining LSWT trends (Pareeth et al. 2017). Recognizing its importance, LSWT has also been included by the Global Climate Observing System (GCOS) in the list of essential climate variables (ECVs) that should be monitored (Lieberherr & Wunderle 2018).

A global synthesis of LSWT long-term observations showed that lakes worldwide warmed at an average rate of 0.34°C per decade between 1985 and 2009. In general, lakes in cold-winter regions (mean air temperature <0.4°C) are warming faster than those in warm-winter regions, reflecting in part the intensified increase in air temperature in polar and high-altitude regions. However, lakes in cold regions also show warm-season trends in LSWT that are comparable to or quantitatively exceed air temperature trends.

These trends suggest responses of earlier stratification or additional energy sources at the lakes, such as increased absorption of solar radiation. In some cases, reduced ice cover or less snowfall (and thus snowmelt influences) contributed to greater amounts of available energy and thus to surface water warming and increased evaporation rates (Woolway et al. 2020).

The dataset of a study by Lieberherr & Wunderle (2018) includes 26 European lakes and covers the period from 1981 to 2016. The researchers recorded that the warming trend increased from southwest to northeast Europe. In general, however, a strong heterogeneity of trends within a year was observed across lakes. This suggests that using a single period within a year to determine temperature trends is not representative. It appears to confirm that different seasons do not contribute equally to annual trends. Therefore, a trend analysis based only on summer periods cannot provide a complete overview. In addition, heterogeneity of trends within the lake was found. The location of measurements significantly affects trends. This means that direct comparisons of trends between on-site data and satellite data should be made with caution.

Comparison with local air temperature trends showed that for many lakes the warming of the water was stronger than the local warming of the air. This effect was particularly evident for colder lakes at higher elevations or latitudes. For example, Lake Vättern in Sweden shows a stronger increase in LSWT than in air temperature, while for Lake Bolsena in Italy the LSWT trend is even slightly smaller than the increase in local air temperature.

Phenology of ice on lakes

The phenology of ice on lakes - the time at which the surface freezes or breaks up - provides another indicator of climate change. Ice formation in lakes is largely determined by surface energy balance and air temperature, and is influenced by lake morphology, wind-induced mixing, and other meteorological and hydrological factors. For example, heat loss from the lake surface during ice formation occurs primarily through outgoing longwave radiation. Therefore, initial ice formation usually occurs at night, during cold and calm conditions and clear skies. However, strong cooling and deep mixing are usually also required to „prepare" the lake for surface icing. This is usually done by cold, dry winds that cause heat loss through greater evaporation (Woolway et al. 2020).

Although the processes controlling ice formation and breakup on lakes depend on many interacting meteorological and limnological factors (Gu and Stefan 1990), air temperature is considered the dominant variable for ice formation on lakes (Williams and Stefan 2006). Because the individual physical characteristics of lakes influence freezing processes much more than thawing processes, the timing of ice breakup is a better direct indicator of climate change than the timing of ice formation (Sporka et al. 2006). The use of satellite data to study ice formation processes on lakes at large spatial scales emphasizes the importance of melt timing as an indicator of climate change (Wynne and Lillesand 1993; Latifovic and Pouliot 2007).

However, the relationship between ice retreat and air temperature is often not linear and differs strongly between colder and warmer geographic regions (Weyhenmeyer et al. 2004). The duration of ice cover can also be used as an indicator of climate change when ice cover is intermittent, e.g., when the ice sheet forms and thaws several times during a warm winter (Livingstone and Adrian 2009; Adrian et al. 2009).

Air temperature and its effects on other components of the surface energy balance (especially net radiation) often determine the timing of ice breakup. The increase in air temperature in the weeks prior to breakup is usually the most important factor in breakup. There are also additive effects on heat flux, e.g. through downward longwave radiation, the albedo of snow and ice, and thus the total amount of longwave and shortwave radiation absorbed at the lake surface (Woolway et al. 2020).

Snow depth, shortwave radiation and wind additionally influence ice breakup. A larger snowpack will usually delay breakup due to its higher albedo and greater insulation in the spring. It also contributes to additional ice formation in winter. However, a heavy snowpack in early winter can also reduce the rate of ice formation due to insulating effects. At lake Baikal, for example, cold winters with low snowfall and early ice formation tend to result in thicker ice cover and later breakup. In contrast, heavy snowfall at lakes in Estonia acts as a reflective and insulating layer, leading to later breakup.

Stronger solar radiation favors an earlier onset of snowmelt. The amount of solar radiation absorbed in the lake is partly determined by the height and density of the snow cover on the ice and the translucency of snow and ice. With continued climate warming, the trend toward earlier breakup of ice on lakes is expected to increase significantly. For example, compared to the end of the 20th century, ice breakup is expected to occur 10 to 25 days earlier in the Canadian Arctic and 10 to 30 days earlier in the rest of the Northern Hemisphere (Woolway et al. 2020).

Evaporation

To predict the response of lake ecosystems to climate change, it is important to understand the physical factors that result from evaporation. According to Woolway et al. (2020), evaporation in water bodies directly and significantly alters the hydrologic, chemical, and energetic balance of lakes. The cooling effect of evaporating water affects lake surface water temperature (LSWT), ice formation, vertical stratification mixing, and gas fluxes. It also affects lake water level and expansion, and even regional climate.

Evaporation is energy intensive, consuming about 82% of the global radiant energy available on the Earth's surface (Trenberth et al. 2009; Wild et al. 2013; Woolway et al. 2020). However, the diffuse nature of evaporation lends itself to mass transfer formulations where the evaporation rate in open water is simply proportional to the vapor pressure gradient near the surface and various functions of wind speed and atmospheric stability. While the most direct atmospheric drivers of evaporation in lakes are undoubtedly wind speed and absolute humidity, predicting the vapor pressure gradient in models also requires knowledge of LSWT and ice to calculate the saturation vapor pressure at the lake surface.

Unlike many studies examining the effects of projected increases in air temperature on aquatic ecosystem function, the effects of potential changes in wind speed have not been studied in depth (Adrian et al. 2009). Wind speed is often strongly influenced by spatial components. There are differences between coastal and inland regions (Griffin et al., 2010). For Europe, wind speeds are expected to increase up to 220%. In addition, the frequency of storm surges in northern Europe will increase (Beniston et al., 2007). Wind speed can also be drastically altered by land use, such as afforestation. This, in turn, can alter the thermal regime, especially of small lakes and water reservoirs (Kerimoglu and Rinkle, 2013).

Finally, the timing, intensity, and total volumetric fluxes of evaporation in lakes can also be influenced by numerous lake- and landscape-specific variables, such as water clarity and windbreak effects. The response of water evaporation to climate change is likely to be spatially highly variable due to these complex interacting factors. Nevertheless, overall mean annual lake evaporation is expected to increase by about 16% by 2100 compared to the 2006 to 2015 period (Wang et al. 2018, Friedrich et al. 2018). The largest increases in annual evaporation are expected at low latitudes (annual changes of about 210 mm per year), where evaporation rates are already high (about 1,600 mm per year for the 2006 to 2015 annual mean of lakes between 30°S and 30°N). The increase in evaporation in lower latitude lakes is primarily a response of the surface energy balance to increasing air temperatures and downward longwave radiation, which also cause an increase in LSWT. However, compared to air temperature, the increase in lake surface temperature is attenuated by additional energy losses due to evaporative cooling and emitted longwave radiation, resulting in a weakening of the lake air temperature gradient and reduced sensible heat flux (Woolway et al. 2020).

While changes in longwave radiation, ice cover, and stratification are generally expected to dominate the long-term response of lake evaporation to climate change, other factors must also be considered, especially on shorter time scales. For example, global and regional changes in incident solar radiation due to changes in cloud cover and aerosols (often referred to as solar offsets) contribute to trends in pond evaporation. Like evaporation ponds or pools, lakes are also energy-limited systems, so some lakes may experience increased evaporation in response to solar offset trends, particularly in light of observed changes in LSWT. Although these fluctuations may continue into the future, a general long-term trend in solar radiation is not expected. Similarly, downward trends in wind speed and decreasing evaporative capacity have also been observed.

However, other studies have recently found a reversal of this general trend or even an upward trend in regional wind speed. Therefore, solar- and wind-induced trends in lake evaporation are likely to be very local and variable on short time scales and of smaller magnitude on longer time scales. Changes in atmospheric humidity could also affect evaporation trends, and the specific humidity of the global atmosphere is expected to increase in the future. However, it is unlikely that a moister atmosphere will be able to compensate for the increasing evaporation of rapidly warming land areas and lakes.

Finally, it should be noted that evaporation from lakes is often highly episodic and may be influenced by interannual changes in synoptic weather variability, such as the frequency of cold fronts. Accurate projections of the response of lake evaporation to climate change must therefore account not only for trends in average climate, but also for changes in variability (Woolway et al. 2020).

Interaction of climatic variables with biological factors.

Studies of lakes in alpine regions of Europe note an increase in the occurrence of potentially harmful cyanobacteria such as *Planktothrix rubescens* (Ernst et al. 2009) and *Dolichospermum lemmermannii* (Salmaso et al. 2015) in recent decades. This could be due to changes in local nutrient concentrations and a warmer climate (Monchamp et al. 2018).

A study by Lau et al. (2019) examined high mountain lakes in Norway, Sweden, Finland, and the Faroe Islands. Here, data were collected on at least three biological focal ecosystem components (FECs) - macrophytes, phytoplankton, benthic diatoms, nearshore benthic macroinvertebrates, zooplankton, and fishes - which also included different migratory species and aquatic habitats with different nutrient statuses. Biodiversity patterns of these lakes, distributed along broad environmental and spatial gradients, were analyzed, and possible correlations between their spatial biodiversity patterns and a range of abiotic and geographic variables were examined. The researchers found that the biodiversity of FECs of different trophic levels in northern European subarctic lakes was strongly influenced by climatic variables (mainly temperature and precipitation) determined by geographic position (e.g. latitude) and hydrographic vegetation.

At lower latitudes, representing warmer and wetter climates, the relative abundance of phytoplankton, macrophytes, and fishes -key players in the upstream and downstream control of lake food webs- decreased. However, the abundance of zooplankton and macroinvertebrates -intermediate trophic levels in pelagic and benthic food webs- increased. These results suggest that climate change may displace cold-adapted species with more southerly species, as they are more tolerant of warmer waters (Lau et al. 2019).

The above-mentioned study provides strong evidence that trends in biodiversity of northern European lakes observed by gradients of climate, geographic location, and watershed vegetation were specific to trophic level. Patterns of intermediate trophic levels differed from those of fish and primary producers. Climate, along with temperature and precipitation, was the variable most strongly associated with spatial patterns related to latitude and elevation. Watershed vegetation, which includes both climatic influences and human influences (e.g., land use), was also important and likely regulated nutrient inputs and allochthonous organic subsidies to lakes, ultimately affecting their productivity (Lau et al. 2019).

Woolway et al. (2020) noted that climate change impacts have been observed in lake ecosystems around the world, including changes in water quality associated with increases in phytoplankton biomass and changes in the composition of biotic communities. Rising temperatures lead to major changes in plankton communities, such as increased populations of cyanobacteria and increased production of toxic metabolites. Even in remote lakes, unprecedented abundances of cyanobacteria have been detected, reflecting early ice flow, incomplete mixing, early stratification, and a consequent increased internal nutrient loading. An earlier onset of phytoplankton blooms has been observed in many lakes, e.g., a 30-day shift between 2003 and 2017 at Lake Taihu in China and a 28.5-day shift between 1984-1994 and 20072017 at Lake Köyliönjärvi in Finland.

Increases in chlorophyll and cyanobacteria also often correlate with declining water levels in many lakes and reservoirs, sometimes accompanied by regime changes from clear to turbid water that were sometimes irreversible. At some lakes, increasing stratification influenced by climate change is leading to declines in algal biomass, which has had a negative impact on fisheries yields. Changes in water temperature also affect metabolism, biodiversity, and species invasion.

Changes in weather conditions and precipitation during winter have a number of consequences. For example, changes in the duration, timing, and state of ice cover on lakes will affect biogeochemical cycling, community composition, algal biomass, food web dynamics, and gas emissions, with consequences similar to permafrost thaw. In combination with other environmental changes, the expected wetter climate conditions will result in more turbid lakes due to terrestrial inputs of dissolved organic matter. This has implications for carbon cycling, invasive species, pathogen persistence, and other ecological factors. Climate change, combined with increasing turbidity and more nutrients (eutrophication) in the water, will alter the function and composition of aquatic food webs. Indirectly, then, climate warming is also affecting lake ecosystems through landscape changes, e.g., through increased erosion or dust, which ultimately affects nutrient availability, water quality, and community composition and productivity.

Many of the emerging changes in lake ecosystems are the result of complex interactions of a variety of climate factors, human activities, and lake characteristics. However, the influence of climate is significantly detectable, even in lakes that are heavily impacted by other factors such as oil or gas extraction, deforestation, and invasive species. Anthropogenic influences on terrestrial nutrient cycling are one of the most interacting factors. The combination of increased nutrient inputs and temperature often act synergistically to create lower oxygen (hypoxic) conditions that negatively affect the frequency, intensity, and duration of harmful algal blooms and ultimately biodiversity.

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2.3 Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration

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Most wetlands are natural long-term carbon sinks. The saturation of their soil with water prevents organic matter from being decomposed into carbon dioxide, which would be released into the atmosphere. However, this ecological condition also facilitates the production of methane, a potent greenhouse gas that can offset the climate change mitigation potential of carbon wetlands.

This study aimed to clarify the role of wetlands in mitigating climate change by examining the balance between the cooling effect of carbon preservation in soil and the warming effect of methane emissions. The results revealed that different types and ages of wetlands had varying climate cooling efficiencies. Coastal wetlands, including mangroves and salt marshes, were found to be the most efficient in cooling the climate due to their high carbon storage capacity and the absence of methane emissions caused by the presence of salt in their soil. Inland wetlands, however, exhibited more varied results. Since they lack salt in their soil, they release larger quantities of methane per surface area, which reduces their climate cooling potential. Notably, older inland wetlands were more likely to have a net cooling effect because methane remains in the atmosphere for approximately 12 years, while carbon stored in wetland soils can remain locked up for much longer unless the ecosystem is disturbed. On the other hand, recently restored inland wetlands were found to have a net warming effect. It takes between 57 to 299 years for restored wetlands to transition from net warming to net cooling. Consequently, the climate benefits of wetland restoration can only be realized on a decadal or century time scale, which surpasses the timeframe specified in the Paris Agreement.

The study also assessed the cost of restoring wetlands and their cost-effectiveness in terms of the potential cooling effect they can generate. Mangroves were identified as the most cost-effective wetland type for restoration, primarily due to their low methane emissions and their prevalence in developing countries, where restoration costs are expected to be lower. Inland wetland restoration, however, was considered a more expensive, long-term investment due to their high methane production and release, resulting in limited climate change mitigation benefits in the short term. The discrepancy between the longer-term benefits of inland wetland restoration and the shorter reporting and funding timelines presents a challenge to their inclusion in climate change mitigation strategies. Therefore, conserving existing inland wetland ecosystems is seen as more effective for climate change mitigation than their restoration.

In conclusion, the study emphasizes the complex role of wetlands in regulating atmospheric greenhouse gas (GHG) concentrations. While wetlands generally act as carbon sinks, their ability to cool the climate depends on factors such as wetland type, age, and the balance between methane emissions and carbon sequestration. The findings suggest that coastal wetlands, such as mangroves and salt marshes, as well as millennium-old undisturbed inland wetlands like peatlands, are the most effective in mitigating climate change. Nevertheless, their planetary contribution will remain marginal considering the large amount of greenhouse gas emissions being released by human activities. The study also underscores the importance of wetland conservation, as it is a more cost-effective and efficient approach than restoration in generating a climate cooling effect within the timeline specified by the Paris Agreement.

2.4 Peatland protection and paludiculture as climate change mitigation approach

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Distribution of peatlands

Peatlands occur in at least 175 countries around the world and cover around 4 million km2, or about 3% of the Earth's land mass. In the northern hemisphere, climatic conditions are well suited for the formation of peat, but peatlands also occur in the tropics. In Europe, peatlands extend over an area of more than 593,727 km2 (Tanneberger et al. 2017), in Germany mainly in the northwest and northeast and in the Alpine foothills. Fens are very productive because they are rich in water and nutrients. Raised bogs are supplied exclusively by precipitation and by mineral salts introduced from the air.

Peatland drainage is harmful to the climate

The draining of peatlands and the conventional agricultural management of drained peatlands leads to the decomposition of the organic soil material (peat), which results in high greenhouse gas emissions, especially CO_2. The resulting nutrient release and loss of biodiversity increasingly limit land use options. Organic carbon-rich soils occupy a total of 5.2% of the land area in Germany (about 1.8 million hectares, Tegetmeyer et al. 2021), but only 2% of them still have a naturally wet state. Agriculture on peatland soils in Germany causes annual climate damage of about 7.4 billion euros through drainage and the associated peatland degradation, which is subsidized with EU funds of 410 million euros. Drained peatlands are major sources of agricultural CO_2 emissions. Although peatlands cover only 7% of the utilized agricultural land in Germany, they are responsible for 37% of total agricultural greenhouse gas emissions (agriculture and LULUCF sector, including livestock). This corresponds to around 53 million metric tons of CO_2 eq. per year (UNFCCC: National Inventory Report for the German Greenhouse Gas Inventory 2020). Peat decomposition or mineralization in drained peatlands also leads to high substance releases via ground and surface waters, which contributes to the fact that many lakes and coastal areas in Europe suffer from a high nutrient load and are highly eutrophic. The substance releases from agriculture, both from mineralizing peatlands and from fertilized mineral soils, are the main source of the nutrient pollution of our waters - ground waters, surface waters, coastal waters and lakes.

Another undesirable effect of peatland degradation is the continued loss of height, which amounts to about 2 cm annually. This continued loss of peatland height caused by peat mineralization, slumping, and erosion makes it necessary to deepen drainage ditches, which in turn increases peat extraction and height loss. Any drainage-based use of peat soils means potential loss of productive soils in the long term. The resulting damage to water, land and infrastructure is a major problem – also in the long term from an economic point of view.

Scientific studies show that raising the water levels of peatlands leads to reduced greenhouse gas emissions (Günther et al. 2019). This is an opportunity for climate and nature conservation. Of the approximately 1.8 million hectares of bog and fen soils in Germany, about 50,000 hectares per year should be rewetted by 2050 to reduce greenhouse gas emissions and meet the Paris climate targets. At the same time, nutrient releases into flowing waters would also be greatly reduced. Intact peatland landscapes also benefit specialized and endangered animal and plant species such as e.g. sedge warbler and sundew.

Rewetting and paludiculture as a solution approach

Rewetting contributes to mitigating high greenhouse gas emissions, and the long-term carbon storage function of organic soils can be restored by increasing the water table, which leads to the establishment of peat-forming vegetation. Peatland rewetting can reduce the immense nutrient release of nitrogen and phosphorus from drained peatlands, a key task for river basin management in northwestern Europe and in the catchments of the North and Baltic Seas. Restoration of water-dependent semi-aquatic habitats can achieve both ecological and economic goals. For example, the rewetting of degraded peatlands protects the climate through reduced greenhouse gas emissions combined with positive regional effects of landscape cooling through increased evapotranspiration.

At the same time, peatland rewetting can protect surface waters and ground waters by binding excess nutrient inputs in the rewetted soils (P, N) or eliminating them through denitrification (N). In addition, rewetting prevents further land subsidence and reduces soil erosion.

The improvement in water quality results not only from a reduction in peat mineralization, but also from the uptake of nutrients and pollutants by the peatland vegetation. Many wetland plants have been shown to have a positive effect on water purification (Wissing & Hoffmann 2002). The biomass of rewetted peatlands that have not been additionally fertilized "exports" the nutrients it contains from the system, so to speak. Animal-based forms of use, e.g. grazing wet pastures with extensively kept water buffalo, can also contribute to an improved nutrient balance. Peatland rewetting in combination with "wet agriculture" (paludiculture) can also be profitable from an economic point of view if the biomass that grows up is used in paludiculture and other ecosystem services are rewarded. Paludiculture can thus provide a sustainable alternative to conventional agriculture. The harvested biomass can be used as building and packaging material, as substrate in horticulture, for energy production or as fodder. Rewetted peatlands support the revitalization and maintenance of biodiversity by providing typical habitats for animal and plant species, most of which have become rare.

Fig. 2: Left: Peat moss harvesting. Right: Moldings made from wet meadow biomass and reeds (source: Greifswald Mire Centre)

In wet meadows, reed canary grass, sedges and water buffalo form important factors for sustainable agriculture. Other paludiculture options include reeds, bulrushes, or peat mosses. There could be a large market for material recovery pathways through that encourage the cultivation of climate-smart products. Defibrated reeds, sedges, or cattails can be used as building panels or molding parts. Foam boards made from sedge or grass paper as packaging are further examples of the usability of these products.

Implementation of paludiculture in Mecklenburg-Vorpommern

Peat soils in Mecklenburg-Vorpommern cover about 290,000 ha. or 13 % of the state area and produce, especially by drainage for agricultural use, around 30 % of the total statewide greenhouse gas emissions. Within agriculturally used areas and taking into account legal technical requirements, an area map for paludiculture was created for Mecklenburg-Vorpommern. This distinguishes between "wet meadows" and "cultivated crops". From the point of view of agriculture and nature conservation, paludiculture is possible without restriction on more than 85,000 ha. On further 50,000 ha, paludiculture can be practiced after conservation examination and on another almost 30,000 ha, wet meadows can be cultivated also after conservation examination (Tanneberger et al. 2020), (LM MV). However, there are currently still various challenges for such forms of management, like the lack of eligibility for subsidies for cultivated paludiculture, inappropriate financing instruments, and a lack of utilization structures.

One example of the thermal utilization of wet meadow biomass is the Malchin heating plant. There, hay harvested in midsummer from about 300 ha of wet meadows near Lake Kummerow is burned in a Danish straw incinerator adapted for this type of biomass to generate heat. About 500 households are supplied with heat and hot water by this plant. The BOnaMoor collaborative project (2018-2021) is investigating how to optimize the management of peatlands and the thermal utilization of biomass from wet fens.

Peatland Protection - Approaches in Brandenburg

Due to their ability to store climate-relevant greenhouse gases, peatlands are of outstanding importance in terms of climate protection. And this applies to Brandenburg in a special way, as it is very rich in peatlands. The switch to a management that reduces peat depletion by 2030 and to a climate-neutral management by 2050 are essential elements of the German Climate Protection Plan 2050. According to the federal state target agreement on peatland protection, emissions from German peatlands are to be reduced by 5 million metric tons of CO_2 eq. per hectare and year by 2030, down from 44 million. This is a reduction of around 11.4%. For Brandenburg, this corresponds to around 50,000 hectares of peatland.

On behalf of the state of Brandenburg, the project "Climate Protection and Adaptation through Peatland-friendly Establishment of Reservoir Areas and Water Management in Relation to Peatland Areas of the State of Brandenburg and their Catchment Areas" ("Klimaschutz und Klimafolgeanpassung durch moorschonende Einrichtung der Staubereiche und Wasserbewirtschaftung in Bezug auf Moorflächen des Landes Brandenburg und deren Einzugsgebiete") is investigating the water retention capacity of large-scale peatlands where water balance has been impaired by drainage measures. One goal is to develop strategies and solutions for management adapted to high water levels together with the users and to establish attractive utilization possibilities.

Peatlands combine a variety of ecological, economic and social functions through their diverse ecosystem services, which, however, are not always in harmony with each other. For example, the protection and revitalization of peatlands by raising water levels is desirable from the point of view of biodiversity and climate protection, but it conflicts with the land use that up to now has been accompanied by drainage. In order to reconcile these sectors, innovative approaches for adapted land use are needed, as well as support for agricultural enterprises in the operational adaptation and marketing of the new products.

Against this background, the state of Brandenburg has launched two new funding programs for peatland protection. In the support program for peatland-friendly damming, land users must achieve water levels of no more than 10 cm below ground level in winter and 30 cm below ground level in summer. In return, land users receive annual subsidies in the amount of 387 euros per hectare. In spring 2022, the second climate and peatland protection initiative was launched, which aims to prevent further degradation of peatland soils and to promote conversion to wet peatland use. Within the framework of the planned funding guidelines, investments in peatland conservation and peatland protection technology and management methods are to be supported, as well as the development of new utilization options for biomass-based products.

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3. Impacts of climate change on lakes and wetlands in Europe

3.1 Climate change and Europe's water resources

Technical Report for the PESETA IV Project
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In addition to the already existing pressure on our freshwater resources, climate change may further decrease water availability. In this study, projections of future water resources, due to climate change, land use change and changes in water consumption have been assessed using JRC's LISFLOOD water resources model (https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-lisflood).

The results presented are based on 11 climate models which project current and future climate under two Representative Concentration Pathways (RCPs): RCP4.5 and RCP 8.5 emission scenario. RCP4.5 may be viewed as a moderate-emissions-mitigation-policy scenario and RCP8.5 as a highend emissions scenario. A 30-year window around the year that global warming reaches 1.5°C, 2°C and 3°C above preindustrial temperature has been analysed and compared to the 1981-2010 control climate window (baseline). The 1.5°C and 2°C warming scenarios are explicitly considered in the Paris Agreement, while a 3°C global warming is a scenario that could be expected by the end of the 21st century if adequate mitigation strategies are not taken.

First, we performed future projections without socio-economic developments to show the effect of climate change only. Next, an integrated assessment is performed including future changes in land use, water demand and population. This allows us to disentangle the effects of climate and socio-economic changes.

In general, the climate projections reveal a typically North-South pattern across Europe for water availability. Overall, Southern European countries are projected to face decreasing water availability, particularly Spain, Portugal, Greece, Cyprus, Malta, Italy and Turkey. Central and Northern European countries show an increasing annual water availability.

Current pressures on water resources are exacerbated in Southern Europe

To demonstrate the ratio between water demand and consumption versus total water availability, we use the Water Exploitation Index Plus (WEI+) (consumption ratio) as an indicator for water scarcity. The WEI+ is defined as the total water net consumption divided by the freshwater resources of a region, including upstream inflowing water. WEI+ values have a range between 0 and 1. Different gradations of water scarcity are determined. Values below 0.1 denote "low water scarcity", values between 0.1 and 0.2 denote "moderate water scarcity", "water scarcity" when this ratio is larger than 0.2, and "severe water scarcity" if the ratio exceeds the 0.4 threshold (Faergemann, 2012).

Results show an intensification and a longer duration of water scarcity in the EU under global warming, specifically in the Mediterranean countries. To demonstrate this, the change in water scarcity days (WEI+ > 0.2) relative to the current climate is presented in Fig. 1 for the three warming levels. Water scarcity is projected to gradually increase in duration from current climate towards the 3°C warming level in the Mediterranean regions, especially in the Iberian Peninsula. Here, water scarcity can increase up to more than 1 month per year for the 3°C warming levels compared to current climate. Furthermore, many areas in the Mediterranean regions are projected to have a WEI+ close to 1.0 (not shown here), meaning that all possible (annual renewable) freshwater is being used. In several of these areas, groundwater amounts are depleting.

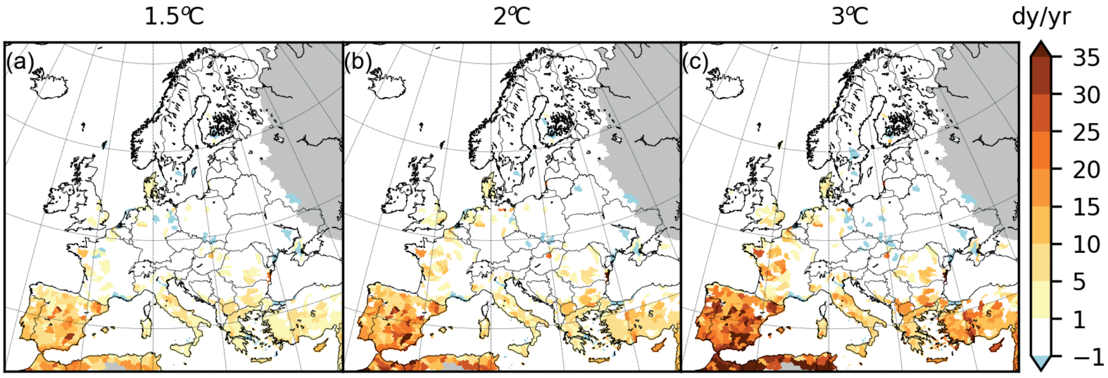

Fig. 3: Projected change in water scarcity days (WEI+ > 0.2) in a year compared with present day for a global temperature increase of (a) 1.5°C, (b) 2°C, and (c) 3°C. The results of both the 1.5°C and 2°C warming levels are based on the average of the 11 climate model simulations from both the RCP4.5 and RCP8.5 emission scenarios, while the results of the 3°C warming level are solely based on the 11 simulation of the RCP8.5 emission scenario.

Number of people exposed to water scarcity

An example of putting water scarcity into a societal perspective is to estimate how many people and economic activities are exposed to different gradations of water scarcity. Averages of monthly WEI+ values are calculated for current climate (1981-2010) and for the 30-yr warming periods centered on the year global mean temperature exceeds 1.5°C, 2°C and 3°C for both the RCP4.5 and RCP8.5 emission scenarios. In the case of the simulations without socio-economic developments the results are overlaid with the population and Gross Added Value (GVA) of 2010. The results of the simulations with socio-economic developments are overlaid with the population and GVA of 2050. As a 3°C scenario is not realistic in 2050, only the 1.5°C and 2°C warming period are considered within the simulations with socio-economic developments. Here, in Fig. 4, we show the ensemble mean of the "static" simulations that shows the effect of climate change only.

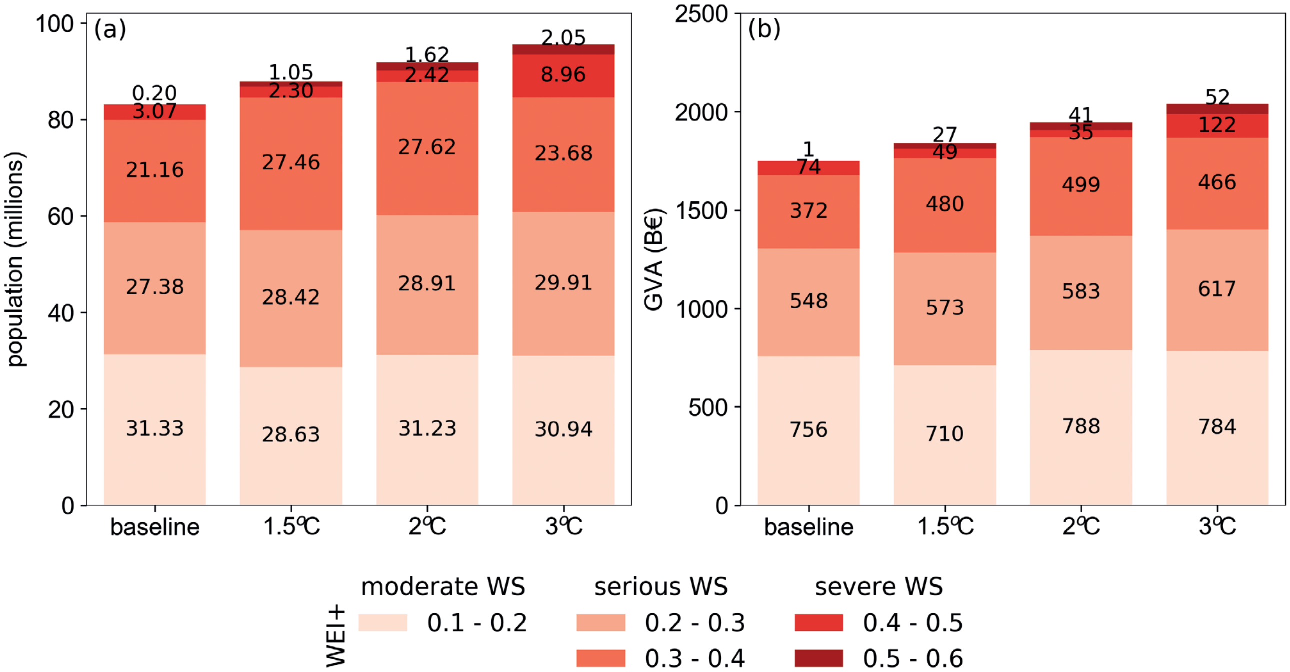

Fig. 4: Projected number of (a) people living and (b) economic activity exposed to different gradations of water scarcity (WS) in the EU+UK solely due to climate change for the baseline and under the different warming levels.

Our projections show that in the EU climate mitigation can considerably reduce the number of people and economic activity exposed to severe water scarcity (WEI+ > 0.4), which is in accordance with stress or even clearly unsustainable use of water resources. In the EU+UK, around 51.9 million people and 995 €billion economic activity are at present exposed to water scarcity (WEI+ larger then 0.2), and 3.3 million people and 75 €billion economic activity to severe water scarcity. Even if we manage to "pursue efforts" to 1.5°C global warming the people and economic activity exposed to water scarcity could still increase with 7.4 million and 134 €billion compared with present climate, but the number of people and economic activity exposed to severe water scarcity, although facing intensified and longer duration of severe water scarcity, remain constant. If not, with unmitigated climate change (3°C), an additional 7.7 million people and 99 €billion economic activity are projected to be exposed to severe water scarcity.

When demographic changes are taken into account, in general the additional number of people exposed to water scarcity is increasing due to population growth in some countries (such as France), but decreasing in other countries due to a projected population decline in countries which are also exposed to severe water scarcity (such as Greece). The projections of the economic activity have a major effect in amplifying the water scarcity in the EU as the economic activity is growing in all EU countries. In general, the number of economic activity exposure can increase to two-fold compared with static economic activity.

If water demand stays at current usage levels and without significant water saving efforts, the warming climate and reduced precipitation in the Mediterranean will cause extreme increases in water scarcity. The people already exposed to water scarcity in current climate will encounter much more intense water scarcity. In addition, many people are projected to be exposed to severe water scarcity in an unmitigated climate.

Adaptation

The severity of impacts under the 1.5°C, 2°C and 3°C warming levels suggests that various adaptation mechanisms will be needed to lessen the effects of climate change on European water resources, in particular in the Mediterranean region. A number of planned adaptation strategies could be targeted at irrigation practices to lower pressures on water resources, e.g. increase irrigation efficiency. Several irrigation efficiency increase efforts are planned within the Water Framework Directive (WFD) Programs of Measures. Water pricing for irrigation water – groundwater, surface water, or re-use of treated waste water, as well as pricing for industrial water and public water, could create incentives for users to consider water savings. Irrigation efficiency could be increased by changing irrigation methods (e.g., from sprinkling to drip irrigation), but this is likely to only be feasible when irrigation water has a price. Furthermore, deficit irrigation strategies may lead to substantial water savings, with only limited reductions in crop yields. More efficient cooling technologies could lead to a reduction in water use for producing energy. In addition, shifts from conventional energy production (coal) to renewable energy production could reduce cooling water demand and net water consumption (Magagna et al., 2019). Changing national or regional water allocation regulations could alleviate water scarcity episodes. In more extreme cases, one might consider stimulating a change to crops that have a smaller (irrigation) water requirement, and critically evaluate subsidizing crops in water scarce areas.

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3.2 Climate and eutrophication impact on lakes in Estonia

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Estonia has nearly 2000 lakes that form 4.9% of its land cover making it the fourth richest country by lakes in Europe. Lake Võrtsjärv, a large and shallow lake (270 km2, mean depth 2.8 m) with a remarkable climate-induced variability in hydrology and water chemistry, is one of the most intensively long-term studied lakes in Europe. Together with the interconnected Lake Peipsi (3,555 km2, mean depth 7.1 m), the two lakes (Fig. 1) provide a perfect model system to study the impacts of climate change on shallow lake ecosystems.

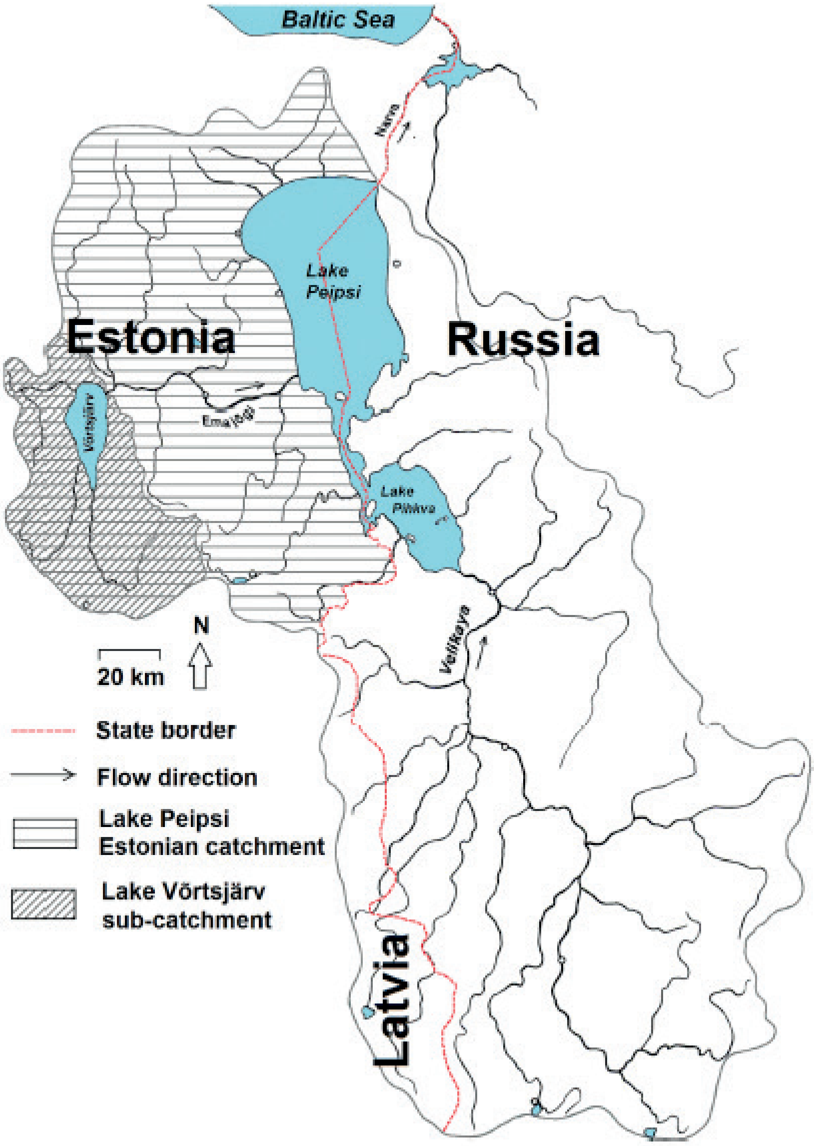

Fig. 5: Location map of Lakes Võrtsjärv and Peipsi (Nõges et al. 2020)

In the period 1961-2011, the surface water temperature in April increased by 0.48°C per decade in Peipsi and by 0.28°C per decade in Võrtsjärv, the increase in August was 0.40°C per decade in both lakes. The deeper Lake Peipsi has later ice-on and earlier ice-off, whereas both dates show higher temperature sensitivity than in Võrtsjärv. As a consequence, an increase in the average November-March air temperature by 2°C would presumably halve the ice cover duration in Peipsi, but would shorten it only by about 20% in Võrtsjärv (Nõges & Nõges 2014).

Continuous buoy measurements and direct emission studies showed that carbon (C) binding and emission are roughly balanced in the pelagic area of Võrtsjärv. The lake receives annually 250-420 g organic C per m2, 65% of which originates from phytoplankton production, 15% from aquatic macrophyte production and 30% from the catchment. Presently C from autochthonous (internal lake) sources exceeds about twice the C from allochthonous (external catchment) sources (Fig. 2). If present climatic trends continue, the winter runoff will increase. Doubling of winter runoff will double also the dissolved organic C (DOC) loads, which will equalize the allochthonous C sources with the autochthonous ones. The rate of photosynthesis is also expected to increase with climate warming, but the increase is much smaller. Sedimentation accounts for approximately 15%, outflow for 20% and respiration for 65% of organic C losses in Võrtsjärv. The increasing DOC load from the catchment together with increasing temperature that stimulates respiration rate more than the rate of photosynthesis, leads to the prevalence of heterotrophy and worsens oxygen regime for fish (Nõges et al. 2016).

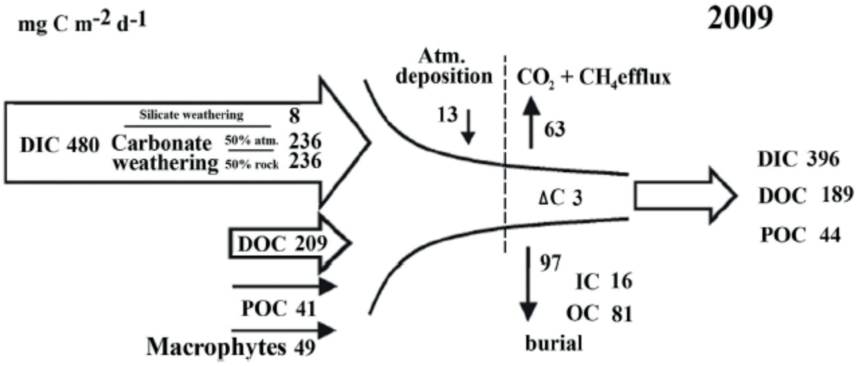

Fig. 6: Carbon budget of Lake Võrtsjärv in 2009 (Nõges et al. 2016).

Estonian lakes have experienced heavy nutrient loading in the 1970s-80s and their rapid decline in the early 1990s, after the collapse of the soviet type extensive agriculture. As the catchment nitrogen (N) loading decreased faster than phosphorus (P) loading, the N/P ratio decreased and in some lakes water blooms re-emerged causing summer fish kills. Our studies suggest that the decadal rise of blue-green algae (cyanobacteria) in shallow lakes lies in the interaction between cultural eutrophication and global warming which bring in-lake physical and chemical conditions closer to cyanobacterial optima (Cremona et al. 2018). The dominating blue-green species in turbid Võrtsjärv are mostly light-limited and the relationship with N/P stoichiometry is indirect while frequent N limitation in the deeper Lake Peipsi favours N2-fixing species (Nõges et al. 2020). Moreover, our recent study (Janatian et al. 2019) showed that as a result of atmospheric stilling over the Northern Hemisphere, the bottom sediments were considerably less disturbed in Võrtsjärv since 1996, bringing about an increase in phytoplankton biomass despite reduced nutrient levels. The declining amount of suspended sediments opened a "light niche" which was capitalized and filled by the light-limited phytoplankton community, suggesting that wind stilling is another global factor, complementary to climate warming, that counteracts eutrophication mitigation in lakes. Our modelling revealed that the combined rise in lake water temperature and pH coupled with the still high availability of P in the water column enabled a steady growth of cyanobacteria biomass during the last decades in Võrtsjärv.

Several fish-kills have been documented in both Estonian large lakes (Nõges et al. 2007). In Võrtsjärv fish-kills occur mostly in wintertime due to the depletion of oxygen. In low-water years, the amount of oxygen trapped under the ice is small due to smaller lake volume and could be depleted under long-lasting ice cover. In Peipsi, high water temperature and algal blooms could result in massive summer fish kills. Intensive photosynthesis produces much oxygen during the day, at night algal masses consume this oxygen and a deficiency could occur. Such large scale diurnal fluctuations of oxygen concentration harm fish and make them more susceptible to other stressors, such as high water temperature, high water pH caused by intensive photosynthesis, and elevated concentrations of ammonium (NH4+) released during the decomposition of organic matter. At high pH (>9), most ammonium is converted to toxic ammonia (NH3) that also can kill fish. Moreover, cyanobacterial toxins can also harm fish populations (Fig. 3).

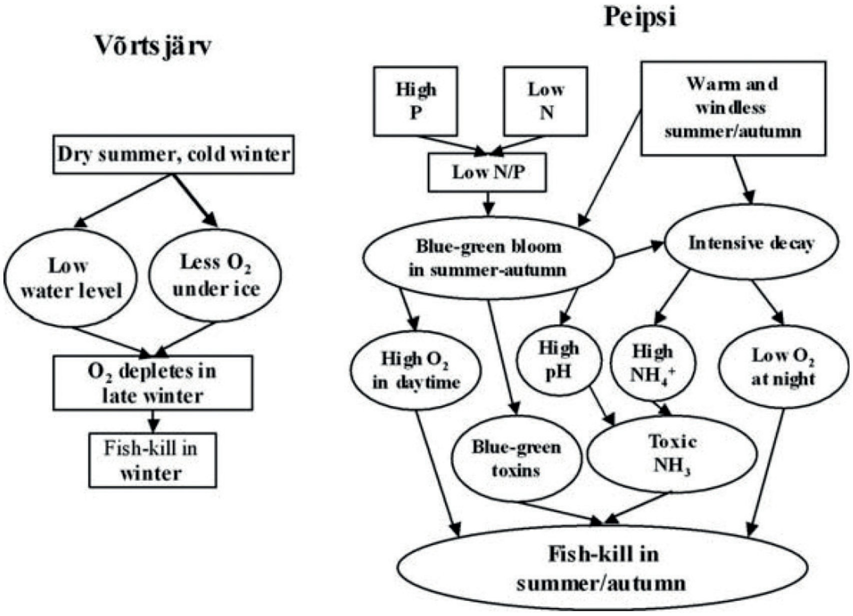

Fig. 7: Schematic explanation of causes of fish-kills in lakes Peipsi and Võrtsjärv (Nõges et al. 2007).

At a global scale, the continuation of warming trends and eutrophication could lead to more frequent harmful cyanobacteria blooms and fish-kills in shallow eutrophic lakes (Cremona et al. 2018). As climate warming reinforces eutrophication phenomena in lakes by increasing internal nutrient loading and favours bloom-forming cyanobacteria, more stringent measures would be needed to further limit nutrient loads (especially that of P) to lakes through improved wastewater treatment and increased efficiency of fertiliser application (Nõges et al. 2020).

Acknowledgements

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3.3 Climate impact and risk analysis for Germany

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If climate change continues, the risks from heat, drought and heavy rainfall throughout Germany will increase sharply in the future. This is shown by the results of the federal Climate Impact and Risk Analysis, which was presented by the Federal Ministry for the Environment and the Federal Environment Agency on June 14, 2021. The damage will have a domino effect, spreading from ecosystems that are already heavily polluted, such as soils, forests and waters, to humans and their health. The analysis examined more than 100 climate change effects and their interactions, and identified a need for very urgent action on about 30 of them. These include deadly heat stress events, especially in cities, water shortages in the soil, and more frequent low waters with serious consequences for all ecosystems, agriculture, forestry, and the transport of goods. Economic damage to structures from heavy rainfall and (flash) flooding has also been studied, as well as species composition change caused by gradual temperature increases, including the spread of disease vectors and pests.

So far, only a few regions in Germany have been very intensively affected by heat, drought or heavy rain. With strong climate change, many more regions would be confronted with these effects by the middle of the century. The west and south of Germany would experience the strongest climate change. The southwest and east would have the most frequent climatic extremes. Rivers and river valleys could be affected by consequences of water-specific risks such as low and high water. On the coast, sea-level rise hazards would increase significantly in the second half of the century. If climate change were strong, by the end of the century the whole of Germany would become a hotspot for climate change risks.

The study was commissioned by the German government and carried out by a scientific consortium with the involvement of experts from 25 federal agencies and institutions from the „Climate Change and Adaptation“ network of authorities. The results of the study are an essential basis for the further development of the German Strategy for Adaptation to Climate Change (Deutsche Anpassungsstrategie an den Klimawandel - DAS). Within the framework of the DAS, climate data and projections are made available via the German Climate Change Portal www.klivoportal.de.

The Climate Impact and Risk Analysis 2021 was published in a summary and 6 sub-reports, in which the 102 climate impacts and 13 fields of action were examined and evaluated with regard to climate risks, adaptation options and need for action in various clusters. Here, we briefly discuss the findings of the analysis, in particular sub-report 3, which presents risks and adaptations related to water. The report makes the following statements, among others:

Key statements on “low water levels”:

- The modeling results of the low water flow for the scenario RCP8.5 are widely scattered
- In the optimistic case (85th percentile), the model results show predominantly no aggravation for both the middle and the end of the 21st century. However, the currently observed developments (1989 to 2018 period) are on a much less favorable path. Extreme single years and episodes are possible in each scenario.
- For the pessimistic case (15th percentile), substantial decreases in low water flow were calculated especially for the second half of the 21st century. This applies to the Moselle, the Neckar and the Mulde for the mid-century and to almost all rivers for the end of the century. The most significant changes are projected for parts of the Rhine.

Key statements on “high water levels”:

- Extreme flood events repeatedly cause great damage and endanger human lives. The climatic, hydrological and hydrodynamic preconditions for their occurrence are very diverse and cannot be generalized.

- For the RCP8.5 scenario, most of the modeled discharges indicate an increase of flood water flow especially in today's rain-dominated regions of Germany (low mountain ranges, eastern Germany), independent of the flood indicator considered.
- The development of extreme and damaging flood events (HQ100 and higher) is subject to a variety of individually combined factors, depending on the type of event, which can only partially be projected into the future for longer periods of time and are still the subject of research.

Key statements on "damages to water-bound habitats and wetlands":

- Wetlands have already been severely degraded (in terms of area and quality) through drainage and subsequent intensification of land and water use. Climate change is an additional threat and is leading to increased drying of wetlands and streams due to prolonged (spring) dry periods and high temperatures, incrementing the risk of further decline and degradation of wetland habitats.
- In running waters (streams, rivers, etc.), suitable habitats and populations of certain fish species such as grayling and trout are declining due to rising water temperatures, and an increasing dispersal of lower riverine species (potamal) to higher water sections is occurring. At low levels and flow rates, waters heat up more quickly, leading to greater oxygen consumption that can cause non-mobile species to lose their habitat. Species bound to warm waters are expected to benefit.

When considering transformative adaptation opportunities, it is discussed that „Opportunities for transformative adaptations to mitigate damage to water-bound habitats and wetlands are evident in the range of land uses for the areas in question. For example, increasing the size of water-bound habitats could be considered. However, this would require a change in the land use pattern of the affected and adjacent areas (Hartje et al. 2015). To implement conservation measures, it would therefore be necessary to purchase large-scale areas, which could be transformed through restoration or rewetting measures. However, this would inevitably lead to conflicts of interest. In addition to a complete transformation of such areas into protected areas, a switch to alternative, nature-friendly forms of land use could also be considered. For example, it would be possible to promote the planting of water-tolerant plant species in rewetted areas through cultivation methods such as paludiculture (Hartje et al. 2015; Wichmann et al. 2020; Ziegler 2020)."

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3.4 Lake Monitoring since 1991: 45 water bodies in Holstein Switzerland and Plön (Schleswig-Holstein, Germany)

Edith Reck-Mieth. Lake Monitoring Program of the Plön District, District Administration of Plön, Office for Environment, Germany

The Citizen Science Project „Lake Monitoring since 1991 - Information on 45 water bodies in Holstein Switzerland, Plön District SH" is sponsored by „Wasser Otter Mensch e.V. - Verein für Ökosystemschutz und -nutzung". From the lakes covered by the project, including the two largest lakes in Schleswig-Holstein, the Großer Plöner See and the Selenter See, about 2/3 have a water surface smaller than 50 ha and are therefore not in the focus of the EU Water Framework Directive. The program includes stratified as well as unstable stratified lakes, bistable lakes and shallow waters. The recording of the visibility depth as well as the taking of water samples has been carried out under comparable conditions since 1991.

As part of the monitoring, water samples are currently being taken at 48 measuring points as parallel as possible to the full autumn water circulation. The following parameters, among others, are determined by scientifically recognized laboratories:

- the nutrients nitrogen and phosphorus
- organic carbon
- the pH value
- the conductivity

The visibility depth is currently measured weekly by dedicated citizens during the vegetation period or beyond at 35 lakes with a Secchi disk (white Secchi disk according to DIN EN ISO 7027-2:2016). This is a recognized measuring method that is used worldwide. The lake monitoring received international recognition through the data storage of more than 32,000 visibility depths on the specially secured server of the environmental database of NOAA (National Oceanic and Atmospheric Administration), the weather and oceanography authority of the United States.

Since 1991, more than 40,000 visibility depths have been recorded by committed citizens as an indicator of water turbidity and algae development, which can be tracked graphically on the website www.seen-transparent.de. Prof. Winfried Lampert, former director of the Max Planck Institute for Limnology (lake science) and initiator of the lake monitoring, evaluated the summer visibility depths occurring in the period from 1991 to 2010 (week 28-37, mid-July to mid-September) and determined that „the lowest visibility depths of the 20 years" were measured across all lakes in 2003.

How do the visibility depths of the „summer peaks" of 2018 to 2020 compare to the exceptionally warm summer in 2003? Surprisingly, the summer visibility depths (week 28-37) of these years show extremely opposite trends: since the start of monitoring 30 years ago, the lowest visibility depths were recorded in 2003 and 2018, and the greatest summer visibility depths were recorded in 2020 and 2019. These opposite patterns of visibility depths occur in shallow lakes like e.g. Bothkamper See as well as in deep, stably stratified lakes like e.g. Großer Plöner See.

In the final report (volume 2) „10 years of lake monitoring in the district of Plön 1991-2000" the results of an analysis of the weather characteristics that accompanied the minimum and maximum visibility depths in the corresponding period of ten years were published. Here, too, it is shown that the mean air temperature in the summer months is not of dominant importance for the development of the summer visibility depth. Erosion processes in the catchment area of the lakes and (theoretically) the temporal proximity of the precipitation event to the individual fertilizer applications seem to be decisive for algae development and for the visibility depth in summer. In particular, special weather conditions in temporal proximity to the first fertilization of the fields in the respective catchment area promote erosion-related nutrient inputs. Mainly in the first half of March, parts of the applied fertilizers seem to be mobilized by precipitation, especially after a preceding dry phase characterized by low soil moisture, and to be washed off from the fields and enter the water bodies through furrows. Only weeks after the input, the phosphate that often limits algae production is transformed into a bioavailable form and can cause increased algae growth and minimal visibility depths in summer. Extreme precipitation events with different regional and small-scale focal points can lead to increased eutrophication with the known negative effects on the lake eco-system such as oxygen deficiency.

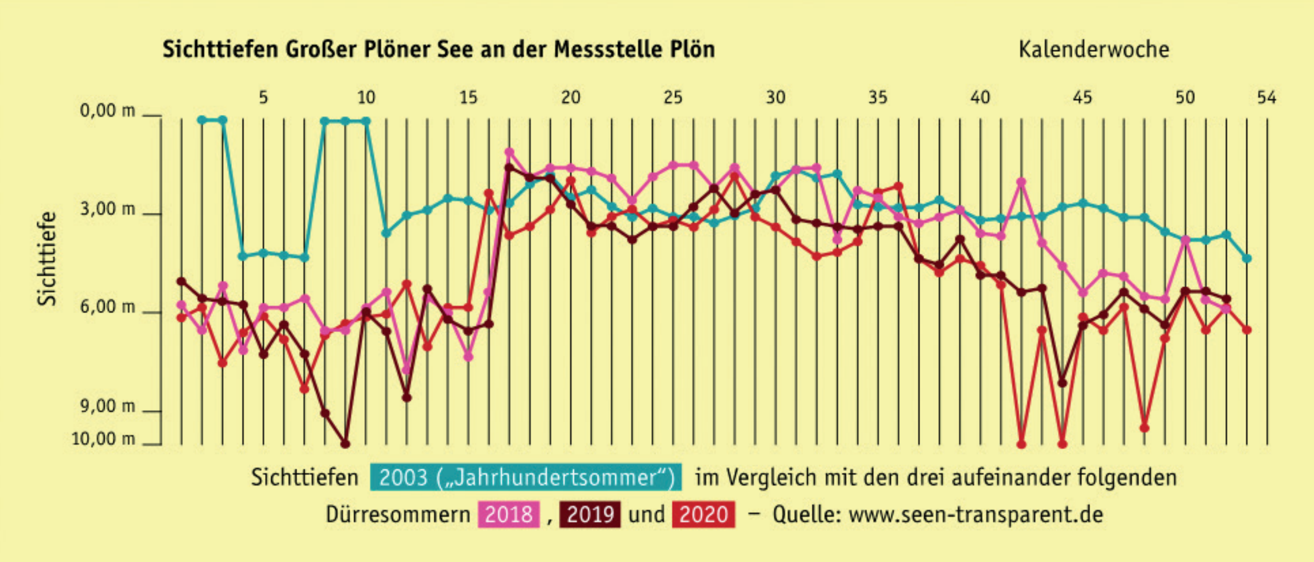


Fig. 8: Measurement of the visibility depths as indicator of the water turbidity and algal development at the measuring station Plön/SH of the Großer Plöner See (Source: www.seen-transparent.de)

Inland waters represent sensitive indicators of environmental changes that have already occurred. Are extreme weather situations in the years of the „summer peaks" 2003, 2018, 2019 and 2020 as well as the successive occurrence of the lowest and highest summer visibility depths in 30 years - simultaneously in different lakes of the region - a possible effect of climate change and, depending on the case, a consequence of drought or of extreme erosive precipitation events?

By comparing the data and evaluating the water analyses carried out since 1991 and the recorded visibility depths, and by assessing the temporal shift in the onset of the clear water stage, the spring and summer blooms and their duration, it will be possible to better assess the consequences of climate change to be expected in the future, and to specifically design protection measures at the lakes included in the monitoring program and in their catchment areas.

3.5 Recent extremes of Lake Balaton's water management

Gabriella Kravinszkaja and Erzsébet Szeiman. Central-Transdanubian Water Directorate, Department of Hydrography and Data Warehousing, Hungary

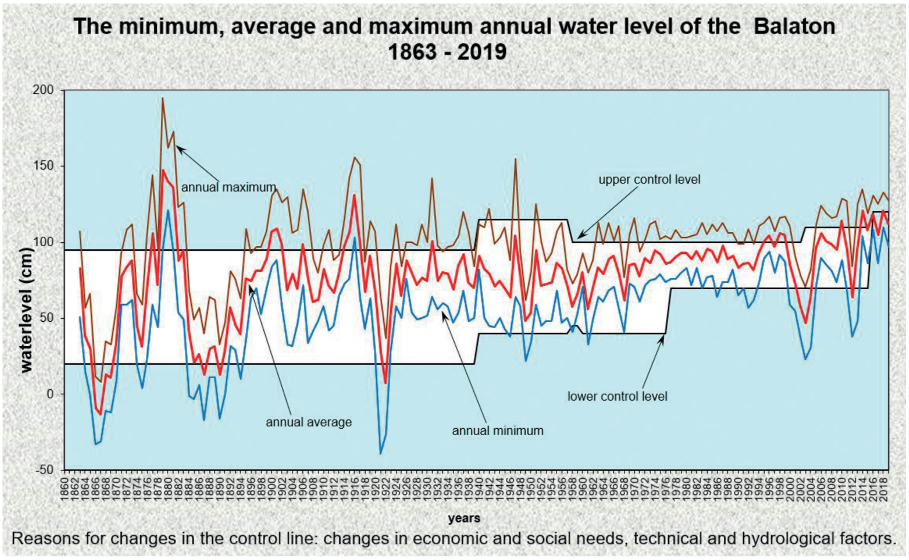
Lake Balaton with its surface area of 600 km2, an average depth of 3.4 m and a water volume of around 2 km3 is the largest shallow freshwater lake in Central Europe. Balaton - like most shallow lakes - is characterized by a high sensitivity to environmental changes in both water quantity and quality. The overtime changes in the amount of water in the lake are determined by natural factors. The result of water management processes is reflected in the change in the water level of the lake.

Until 1863, the water level of Balaton was developed under very different hydrological conditions. These were as follows:

- The difference from today's vegetation and cultivation of the catchment area
- Unregulated incoming streams feeding the lake
- The original state of Kis-Balaton, Nagyberek and Tapolca Bay (swamp, almost continuous water cover)
- The limited discharge capacity of the Sió Valley, the lack of sluices

The outflow of the lake through the Sió Canal has been regulated since 1863. Water levels after 1863, which have been measured regularly, are still showing fluctuation, which are smaller than before (Fig. 1). The multiple reconstruction of the Sio-sluice and the expansion of the water carrying capacity of the Sió bed made it possible to gradually modify the water level control, which meant narrowing and raising the regulation level. The extent and duration of water discharge from the lake is determined by the current water management needs and the water level regulation regime.

The current water level regulation has been in force since 2015. According to this, the permissible upper control line of the water level of the lake is 120 cm, the previous minimum (70 cm), which was basically determined by the development of meteorological and hydrological factors, was abolished.



Reasons for changes in the control line: changes in economic and social needs, technical and hydrological factors.

Fig. 9: Minimum, average and maximum annual water level of Lake Balaton from 1863 to 2019.

The input side of the Balaton's water management balance includes precipitation falling on the surface of the lake (Fig. 2) and inflows (about thirty permanent and twenty intermittent watercourses, the largest of which is the Zala River, which provides about half of the inflow of the lake).

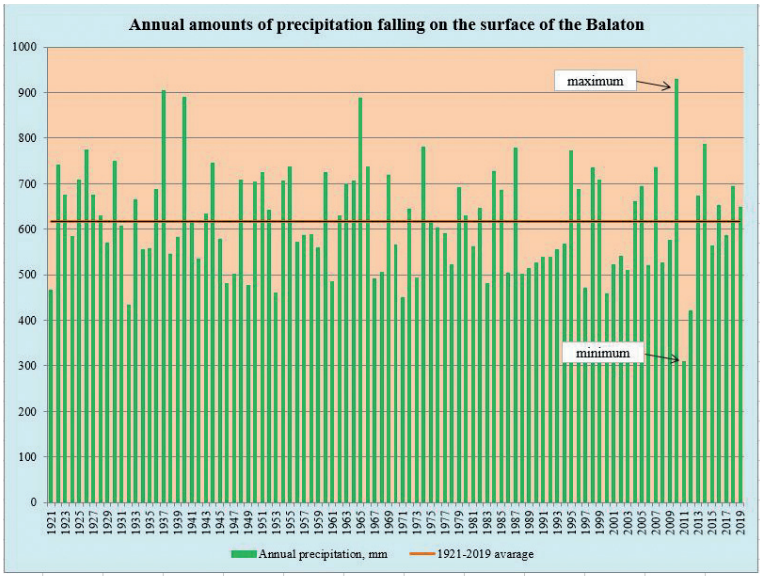
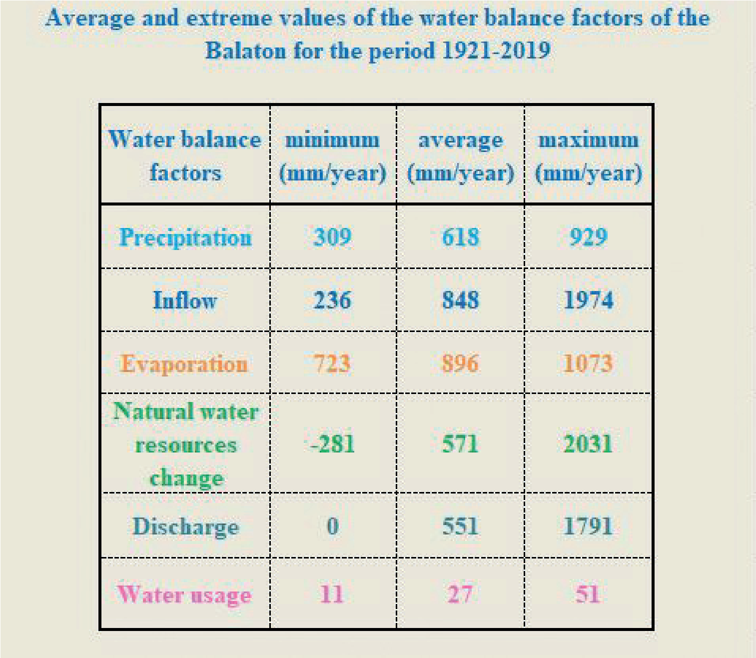


Fig. 10: Annual amounts of precipitation (mm) falling on the surface of Lake Balaton.

The output side of the water balance is evaporation, outflow (through a water discharge sluice that provides water level control) and water usage which directly affects the lake water supply (as a resultant of water abstraction and water input). For the analysis of the water management of Balaton, audited, reliable monthly and annual water balances have been available since 1921. This means that we currently have 99-year (1921-2019) time series for every water balance factor.

Fig. 3 summarizes the average and extreme values of the water management factors determining the water circulation of the lake.



Average and extreme values of the water balance factors of the Balaton for the period 1921-2019

Water balance factors	minimum (mm/year)	average (mm/year)	maximum (mm/year)
Precipitation	309	618	929
Inflow	236	848	1974
Evaporation	723	896	1073
Natural water resources change	-281	571	2031
Discharge	0	551	1791
Water usage	11	27	51

Fig. 11: Average and extreme values of the water balance factors of Lake Balaton for the period 1921-2019.

Since the 1970s - compared to previous periods - there has been a greater number of drier-than-average years. In the same period, the appearance of these years (3, 7, 4, 9 consecutive years) in year groups deserves special attention. This phenomenon results in a cumulative water shortage, which adversely affects the water circulation of the lake, causing a significant and lasting decrease in water resources and water levels. This phenomenon was observed in the early 2000s, when the annual amount of precipitation falling into the lake catchment area fell short of the average for each of the four years between 2000 and 2003. During this period, a one-year rainfall deficit accumulated.

The inflow is on average the largest and most volatile component of the input side of the water balance. The inflow to the Balaton for many years (1921-2019) averaged 848 mm/year, the lowest annual inflow, 236 mm was recorded in 2012, and the highest, 1974 mm was recorded in 1965 (Fig. 4).

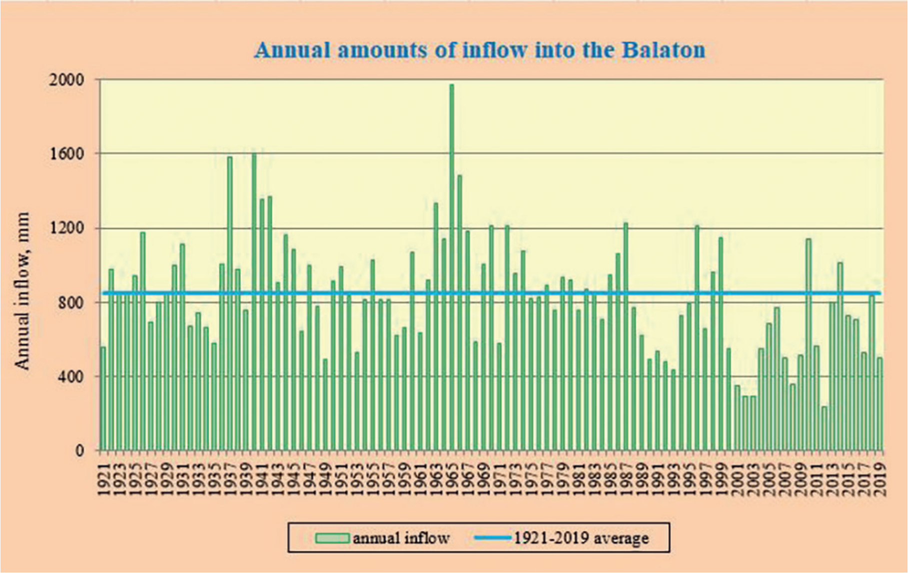


Fig. 12: Annual amounts of inflow (mm) into Lake Balaton from 1921 to 2019.

It is clear from the diagram that the number and duration of deviations from the annual inflow with a negative sign have increased significantly, especially from the first half of the 1980s to the present day.

An unprecedented inflow deficit occurred first for eight consecutive years (1988-1995) and then, after a brief omission, for ten consecutive years (2000-2009) on the input side of the lake's water balance. And after 2010, to this day, the amount of annual inflow has exceeded the multi-year average in a single year. The average value of water use (social factor) for the whole period is 27 mm per year. The lowest value (11 mm) occurred in 2014 and the highest (51 mm) in 1989. In the first half of the last fifteen years, the annual values of water consumption were close to the multi-year average, after which the values indicate a definite decrease.

Discharge (social factor) is also characterized by a high degree of variability (Fig. 5). In the extremely rainy year groups (1964–1966), the value of annual runoff was close to 2-3 times the multi-year average. However, in the much drier-than-average years (2001-2004), there was no discharge at all. The decrease in the excess water reserves to be discharged from the mid-1970s also draws attention to the slowdown and decrease in the water exchange activity of the lake.

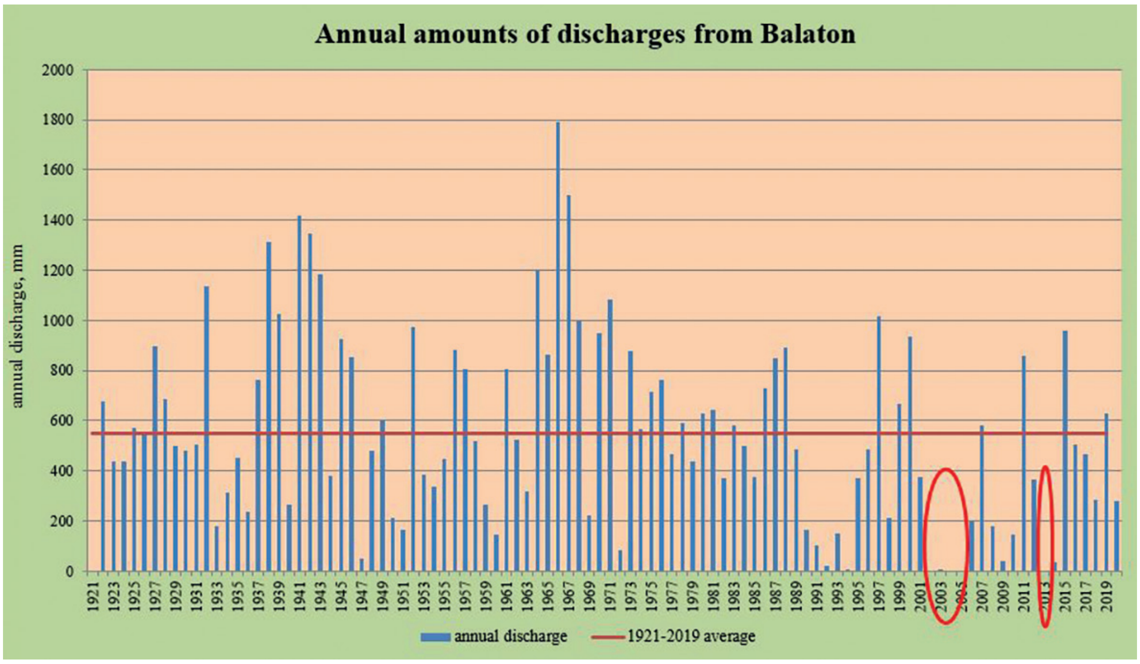


Fig. 13: Annual amounts of discharges (mm) from Lake Balaton from 1921 to 2019.

On the output side of the Balaton water balance, evaporation is listed as a natural factor. Of the natural factors, evaporation is the least variable element. No significant changes can be detected in the time series, which can be called significant. Evaporation from the surface of the lake on a multi-year-average (1921-2019) is 896 mm (Fig. 6).

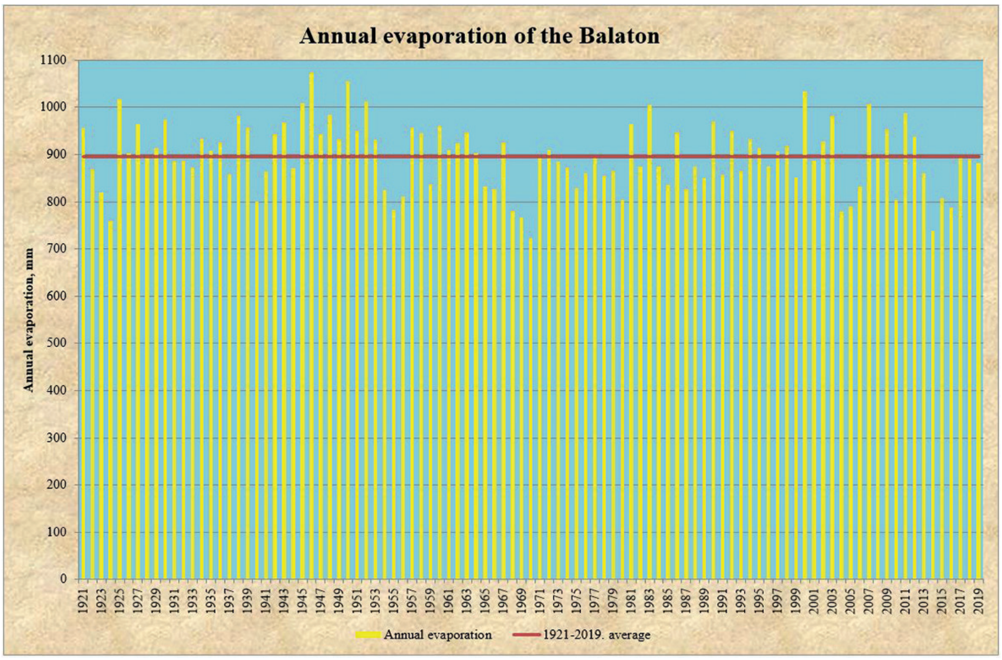


Fig. 14: Annual evaporation (mm) of Lake Balaton from 1921 to 2019.

In the water balance of a lake, the natural water resource change is the algebraic sum of the water balance factors determined by natural factors (in the case of Balaton, precipitation on the lake, inflow to the lake and evaporation from the water surface). This calculated indicator integrates the development of the lake's water balance. Fig. 7 illustrates the time series of the annual change in the natural water resources of Balaton. The strong declining trend since the mid-1970s is conspicuous.

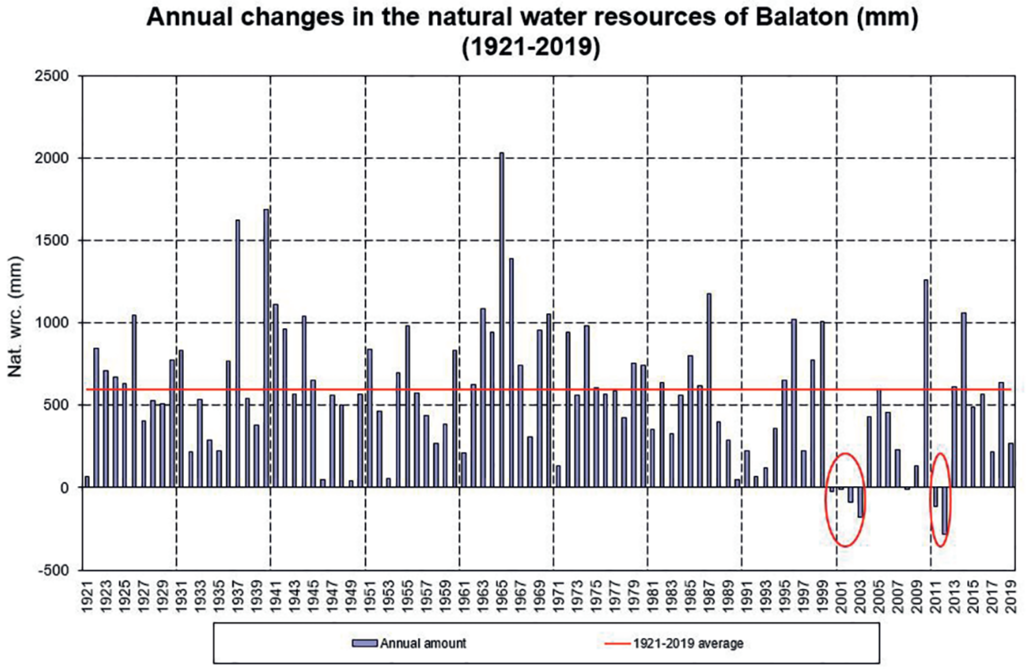


Fig. 15: Annual changes in the natural water resources (mm) of Lake Balaton from 1921 to 2019.

This phenomenon bears a striking resemblance to the change in inflow over the same period. Another noteworthy fact is that between 1921 and 1999, the annual amount of change in natural water resources had a positive sign each year. This means that the natural water intake (precipitation + inflow) of the lake was higher than the natural water release (evaporation). Between the period of 2000 and 2019, there were 7 years when natural intake was less than natural expenditure, so the annual amount of change in natural water resources had a negative sign. It cannot be ruled out with absolute certainty that the extremes of the last decade and a half are already part of a changing climate, stressing that the regional and local (catchment area level) consequences of global warming can only be predicted with great uncertainty.

The extreme climatic values - whether they appear as part of current climate variability or as part of a changing climate - certainly suggest that their appearance has consequences for water management, which can cause an unsustainable condition in the recreational use of Balaton. Possible changes in water level regulation alone cannot compensate for the anomalies in individual water balance elements and their long-term effects.

The continuation of Balaton research and the synthesis of the results is an important process in the foundation of political decision-making. Basic research and evaluation must be carried out before planning any intervention affecting Balaton as an ecological system.

Regular, consecutive occurrences of drought year groups have become significantly more common over the past. This phenomenon - covered with reliable water balances for almost 100 years - used to be much less typical in the Balaton catchment area.

The 120 cm average water level of the Balaton is the regulation water level in force since February 2019. This new level of regulation formalised the practice of the 10 cm water level increase, which began in 2015. This water level change will allow the storage of 60 million m3 of excess water in the lake.

By the fall of 2003, about a quarter of the lake's water volume was missing from the lake. The summer flow of Zala, as the most significant input watercourse, decreased to 200 l/s near the estuary in 2003. The annual change in the lake's natural water resources has become negative for the fourth time in a row, converting

Balaton into a closed basin lake, which we have never experienced in the previous 70 years. At that time an academic working group carried out a scientific examination of the need or rejection of water supply at Lake Balaton. The idea of external water replenishment was basically rejected due to ecological risks. The water level regulation of the Balaton has since been characterized by careful over-regulation. The year 2010 was an extreme hydrological and meteorological year, projecting its phenomena on the Balaton. Cyclones, thunderstorms and extraordinary heavy rainfalls characterized the year, and the amount of precipitation falling on the lake in that year reached the highest recorded value.

Barely seven years after the extremely low average water level, which caused national panic, Lake Balaton poured out. In the low-lying areas of the southern coast (from Siófok to Balatonmáriafürdő) 24 streets, in some cases up to the railway embankment line, were submerged. Taking into account the aspects of regional water management, the intensity of continuous water discharge was limited by the flood waves flowing down on the tributaries of the Sió and on the Danube. In 2010, the effects of all elements had to be considered together and cumulatively in space and time.

The Central-transdanubian Water Directorate, faced with the slow and costly protection of the permanent inland water situation and the technical limitations of the water discharge on the Balaton, has taken several important measures based on the experience of 2010, one of them was that it started the process of the scientific substantiation of the KEHOP (Environment and Energy Efficiency Operational Programme) tender preparations for the modernization of the discharge system of the Balaton. To mitigate the effects of short-, medium- and long-term extreme weather events on the Balaton and its catchment area, a series of decisions have been made by water professionals and politicians over the past twenty years.

The most important findings were:

Water balance analyses related to climate research, as well as drought research, have established the importance of exploiting water storage opportunities in the lake. In response, the Water Directorate raised the upper regulation line of the Balaton by 10 cm, which allows for the storage of 60 million m3 of excess water.

The required "lake flood defenses" continues on the southern shore, the upper reaches of the Sió, the southern shore's groove areas and the Kis-Balaton confirmed the inflexibility of the water level control process and the non-compliance of the available equipment (discharge sluice and lock system, upper Sió canal capacity). To solve this task, the Water Directorate launched a project entitled Modernization of the Balaton's Discharge System within the framework of the KEHOP project.

3.6 Climate change effects on GHG emissions in Mediterranean Wetlands

Influence of the conservation status on carbon balances of semiarid coastal Mediterranean wetlands.

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Permanent freshwater and brackish marshes are the typical wetland type of the Mediterranean Spanish coast. Under natural conditions, these coastal ecosystems could be characterized as wetlands with emergent swamp communities. They are located near the coast with different levels of salinity (in conductivity, from <5 mS cm−1 to 50 mS cm−1). Historical impacts over these ecosystems, such as changes in land use and pollution, water eutrophication, morphological and hydrological alterations, and the effects of climate change, significantly alter their structure and function. Such alterations could consequently modify the carbon budget so that higher carbon amounts might be released to the atmosphere under disturbed situations, thereby diminishing carbon sequestration by these ecosystems. The aim of this study was to assess the carbon balance of Mediterranean coastal wetlands of contrasting conservation status based on a Net Ecosystem Metabolism (NEM) approach, also estimating their Global Warming Potential (GWP) balance.

The main processes related to the metabolic carbon balance were studied in several Mediterranean coastal marshes with different degrees of alteration and in sites restored and managed in different ways. Carbon-related rates and balances were determined seasonally at 4 sites, including two restored sites with different levels of management and restoration and two degraded sites also with different alterations. Carbon associated with greenhouse gases (CO_2 and CH_4) was determined using gas exchange methods for plankton, benthos, and sediments, as well as net production estimations for helophytes. Finally, NEM and GWP balances were determined for the four studied sites, to determine the influence of wetland conservation status, restoration, and management practices on carbon balances.

Globally, although the studied Mediterranean wetlands presented an annual heterotrophic balance in water (based on plankton and benthos metabolism), the NEM balance confirmed the huge carbon capture capacity of this type of wetland, where helophyte production played an important role. However, wetland alterations and management and restoration actions greatly influenced the total carbon balance. Hydromorphological impacts, such as deepening and marine intrusion, decreased helophyte production. Meanwhile, rates of plankton metabolism increased in the altered sites, and rates of benthic metabolism were lower than in the restored sites. Higher content of organic matter in the sediments, linked to alterations as eutrophication and inadequate management, favoured respiratory metabolism, mainly aerobic respiration in the plankton, as well as methanogenesis in anaerobic sediments. These differences among the studied sites revealed the importance of alterations and restoration for carbon exchange. Specifically, a highly altered site showed increased rates of aerobic respiration compared to undisturbed sites, with a decrease in carbon storage capacity to low rates of ~50 g m−2 yr−1. Management practices resulting in instability of the organic sediments favoured degradative metabolism, with release of stored carbon and concomitant increases in CH_4 emissions. Our results indicate that the hydromorphological alterations in these sites may convert healthy ecosystems contributing to carbon sequestration and climate change mitigation into carbon emitting ecosystems. The GWP balance showed how alterations or poor conservation status of wetlands reduces the mitigation capacity. The most altered study site therefore contributed to the release of large amounts of CH_4. On the other side, restoration of the natural wetland structure and function reduced carbon emitting metabolism, by favouring autotrophic processes and reducing greenhouse gases emissions. Freshwater and brackish marshes showed capacity for carbon capture, especially in the restored sites (~950 g m−2 yr−1), with a paramount role of helophytes.

By avoiding external impacts like nutrient discharge or saline intrusion and by restoring a natural condition with submerged macrophyte and helophyte communities, carbon sequestration would increase in the long term because more carbon is recalcitrant and bottom sediments are better oxygenated. The partial removal of organic rich sediments could increase their carbon storage capacity, but soil disturbance could also increase potential for CH_4 release. If planned, sediment removal must avoid altering other ecological characteristics that define a healthy wetland, and the removed sediments could be used, for instance, as soil amendments to replace chemical fertilizers in agricultural practices. This plan would close the circle of nature-based solutions that contribute to important wetland ecosystem services such as climate regulation, food production, and maintenance of productive soils.

Carbon metabolic rates and GHG emissions in different wetland types of the Ebro Delta

Morant, D.; A. Picazo, C. Rochera, A. C. Santamans, J. Miralles-Lorenzo, A. Camacho-Santamans, C. Ibáñez, M. Martínez-Eixarch and A. Camacho. 2020. PloS one 15(4): e0231713. Doi: 10.1371/journal.pone.0231713.

Deltaic wetlands are highly productive ecosystems, which characteristically can act as carbon sinks. However, they are among the most threatened ecosystems, being very vulnerable to global change, and more specifically to sea level rise, and request special attention towards its conservation. Knowing their climate change mitigating potential, conservation measures should also be oriented with a climatic approach, to strengthen their regulatory services. The aim of this work was to study the carbon biogeochemistry and the specific relevance of certain microbial guilds on carbon metabolisms of the three main types of deltaic wetlands located in the Ebro Delta, north-eastern Spain, as well as how they deal with human pressures and climate change effects. The sites selected were representative of natural coastal salt marshes, natural brackish coastal lagoons, and (restored) freshwater wetlands.

The metabolic rates of the main carbon-related metabolisms (primary production and respiration) were assessed and the resulting carbon and global warming potential balances in sites with a different salinity range and trophic status were estimated. The metabolic capacity was also studied and related with the linkage of these emissions with the microbial diversity. Limnological and metabolic in situ studies and experimentation were combined with the assessment of the relative relevance of some microbial guilds, such as those responsible for the methanogenesis. With the results obtained, we tried to define the influence of possible changes in salinity and trophic level linked to the main impacts currently threatening deltaic wetlands, on the carbon metabolisms and greenhouse gases emissions, for a better understanding of the mitigating capacity and their possible enhancement when applying specific management actions.

Metabolic rates showed a pattern highly influenced by the salinity range and nutrients inputs. Freshwater and brackish wetlands, with higher nutrient inputs from agricultural runoff, showed higher carbon capture capacity (around 220–250 g C m^{-2} y^{-1}), but also higher rates of degradative metabolisms (aerobic respiration and CH_4 emissions). Contrastingly, the rates of carbon related metabolisms and carbon retention of *Salicornia*-type coastal salt marshes were lower (42 g C m^{-2} y^{-1}). The study of the microbial metacommunity composition by the 16S RNA gene sequencing revealed the presence of methanogens in the salt marsh, I, where there was significantly more organic matter content in sediment. Salinity inhibition, however, explained the lower respiration rates, both aerobic and anaerobic, and prevented higher rates of methanogenesis despite the major presence of methanogens.

As deltaic ecosystems are demonstrated to be highly active in the carbon biogeochemistry and its link to climate change mitigation, their conservation could be defined also in terms that lead towards increasing the carbon retention. Results obtained in this study suggest the influence of ecological features such as the salinity and the trophic status in the carbon metabolic rates and can be determinant in the microbial activity that leads to greenhouse gases emissions. Knowing these mechanisms, a set of management and conservation measures can be established for the protection of these systems, strengthening their carbon sink capacity, considering the implications of climate change and future predictions. Conservation measures for these wetlands would require, overall, maintaining the sediment contributions of the river basin intending to overcome the regression of the Delta and its salt marshes in a climate change scenario. The improvement of the natural wetlands structure and functions will allow to reduce degradative metabolisms in favour of the productivity and carbon assimilation and storage on a medium/large term. Emergent plant communities, both helophytes and halophytes, can be helpful for the increase of carbon retention. Control and reduction of impacts like freshwater inputs with high nutrients content, and salinization of freshwater and brackish systems, would favour the settlement of natural communities according to the sites characteristics, and the maintenance of the carbon related metabolisms as climate allies. The construction of biological filters to reduce some of these impacts is also beneficial per se, as they can act as carbon sinks, although more efforts have to be considered to reduce CO_2 and CH_4 emissions thereby. In the most saline marshes, contrarily, high salinity levels should be maintained, as in natural conditions, as they have potential methanogens in their sediments capable of activating methanogenesis if salinity levels considerably drop.

Methane emissions in Spanish saline lakes: current rates, temperature and salinity responses, and evolution under different climate change scenarios.

Camacho, A.; A. Picazo, C. Rochera, A.C. Santamans, D. Morant, J. Miralles-Lorenzo and A. Castillo-Escrivà. 2017. Water 9: 659. Doi: 10.3390/w9090659

Wetlands are among the most biologically active ecosystems on Earth, playing an important role in the global carbon cycle. Methane production in wetlands, resulting from anaerobic respiration of organic matter, accounts for an important part of natural sources of methane. Non-CO_2 greenhouse gases, such as methane, can have a high importance for the achievement of climate mitigation efforts if their release to the atmosphere is reduced. Given their global prevalence, how greenhouse gases fluxes from wetlands and shallow lakes to the atmosphere are altered by climate change may have deep implications for the global carbon cycle. Multiple interrelated factors may drive carbon fluxes in shallow lakes and wetlands (e.g., the length of the flooding period, salinity, temperature, and trophic status), in such a way that the biological processes can result in the net capture or release of carbon to/from the water into the sediments and/or, mediated by physical and chemical processes, also from/to the atmosphere.

In this study, five saline shallow lakes from “La Mancha Húmeda Biosphere Reserve” (Central Spain), with contrasting hydroperiods, salinity, and trophic status, were surveyed by in situ and laboratory measurements of methane emission rates, and the main driving factors were studied. We tried to evaluate the sensitivity of methane emissions to the ongoing warming associated to climate change. Measurements of methane emissions were done bi-monthly during a hydrological cycle from samples taken in fixed stations at each lake. The water–air exchange of carbon as CH_4 emission was experimentally measured ex situ from undisturbed sediment cores collected at each sampling event. Sediment core plus water incubations allowed the determination of the release of methane from the studied lakes to the atmosphere, integrating both diffusion and ebullition processes. The temperature and salinity dependence of CH_4 emissions were experimentally determined. Finally, we jointly used the different Radiative Concentration Pathways (RCP) scenarios and related temperature change forecasts with our models of temperature-dependent response of methane emission rates to predict the increase in methane emission rates, by considering the forecasted regional temperature increases under the different scenarios within two temporal frameworks, 2050 and 2070. Additionally, we used these models to estimate the absolute increases in methane release by the hypersaline lakes of La Mancha region.

The studied hypersaline lakes released methane at rates within the lowest range reported for temperate lakes and wetlands, whereas in hydrologically altered lakes that have dropped their salinity these rates were markedly higher. Under controlled conditions, methane production exponentially increased with temperature in all tested lakes. These results were consistent with the measurements of methane release for each lake, which generally increased within the warmer months of the respective flooding periods. Salinity also affected the methane emission rates of the studied lakes. All lakes increased these rates following a power function when their waters were diluted. However, salinity increases asymptotically stabilized these rates around the lowest values already measured in the field experiments.

Models, built with the specific response of methane release rates to temperature regarding the temperature changes expected according to the RCP climate scenarios, predicted significant increases of these rates for the future, which could almost double current methane release for some of the studied lakes under the most pessimistic mitigation scenario (RCP8.5). Overall, our predictions showed that the effect of temperature increase would enhance methane emission rates of the studied saline lakes. The predicted increases in salinity as a consequence of climate change would not significantly mitigate these temperature-increased rates, as under natural conditions they would not impact on the effect of salinity on methane production because further salinity increases over current normal values do not significantly decrease methane release. Thus, the only antagonistic factor with the effect of temperature increasing methane release in these temporary saline lakes would be the reduction of the flooding period, resulting in reducing the overlap between the flooding and warm periods, considering inland saline shallow lakes as naturally temporary systems, which, under well-preserved conditions, usually remain dry during the warmest months.

3.7 The future of Finland's inland waterways

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Water bodies are closely affected by changes in the air and on land. They are nevertheless isolated habitats for many species, which makes it challenging for species to disperse to new areas. As species adapt to climate change, the choice of biotope also matters; conditions in a large water body such as Lake Saimaa are different from those found in a river up in the fells or in a spring deep inside an old-growth forest.

From the land of thousands of lakes

Water covers a tenth of Finland's area. The volume of water is nevertheless small relative to the total area, because the ground surface was worn flat by the ice age and water bodies are therefore shallow (Finish Environment Institute 2010). More than half of Finnish rivers and lakes have a good ecological status, but the small volume of water makes shallow water bodies sensitive to man-made changes in the environment (Finish Environment Institute 2010).

The biodiversity of inland waterways leaves room for improvement. A total of 68% of the biotopes found in inland waterways in Southern Finland are classified as threatened. The situation is better in Northern Finland, and only 3% of biotopes are threatened. The situation is especially worrying as regards fluvial waters – that is rivers and streams – and all fluvial biotopes in Southern Finland are either threatened or near threatened. Lakes fare better, but the majority of biotopes found in lakes have nevertheless been classified as near threatened due to eutrophication and the accumulation of silt deposits, for example. Measures relating to agriculture and forestry, drainage and fertilisation, peat extraction, dredging, and hydraulic engineering and coastal development are among the most common reasons for the endangerment of biotopes found in inland waterways (Ilmonen et al. 2008).

Water bodies provide humans with nutrition, energy, transport routes, and various recreational opportunities. The wellness of aquatic ecosystems is important for the survival of these ecosystem services. Some ecosystem services are dependent on high biodiversity.

Effect of climatic conditions on water bodies

Rainfall affects the volume and quality of water in water bodies, the flow rates of rivers, the likelihood of flooding, the leaching of nutrients and solids into water bodies, and oxygen levels in water, for example. Rainfall determines the hydrological status of water bodies, which is why changes in the volume and temporal distribution of rainfall have a significant impact on the ecological status of water bodies and on biological communities (Poff 1992). Temperature affects stratification, oxygen levels, and the prevalence of different species, as each species has its own thermal optimum (Magnuson, Crowder & Medwick 1979; Heino, Virkkala & Toivonen 2009).

Rainfall and increasing temperature increase eutrophication

Air temperature in Finland is likely to increase by between three and six degrees on average by the end of the current century. Together with the longer growing season, it will increase primary production in aquatic ecosystems. In the future, Finnish waterways will also be affected by rainfall, which is likely to increase by between 12 and 20 percent depending on the climate change scenario. Increased rainfall and heavy rains will increase the leaching of nutrients into water bodies especially during mild winters when there is no layer of vegetation to absorb nutrients and the ground is not frozen. High levels of nutrients accelerate plant growth in aquatic ecosystems, and climate change is expected to increase eutrophication on the whole (Kauppi & Kämäri 1996).

Due to climate change and the resulting lengthening of the growing season (Alahuhta, Heino & Luoto 2010) and increased eutrophication, the volume of vegetation will increase especially along the shores of water bodies. Large emergent aquatic plants will also benefit from higher levels of carbon dioxide in the air and may therefore replace some species that are sensitive to eutrophication. Mass phytoplankton blooms may become more common and appear earlier in the year (Kauppi, & Kämäri 1996). Blue-green algae are believed to benefit from global warming, because their thermal optimum is a little higher than that of other species. They are also capable of fixing atmospheric nitrogen and are therefore not as dependent on the nutrient levels found in water as many other species (Kanoshina, Lips & Luoto 2010).

Increasing productivity increases the volume of organic matter on the lake bed or riverbed as well as the numbers of organisms and their oxygen intake. This affects the composition of biological communities; typically, eutrophication reduces the diversity of species. Fish that benefit from eutrophication include the zander (*Sander lucioperca*) and several species of the carp family (Cyprinidae) (Auvinen 2008). Eutrophication also affects the ability of aquatic ecosystems to act as carbon sinks (Rantakari 2010).

On overturning, flooding, and acidification

As annual mean temperatures rise, winters and the period of ice cover become shorter, the spring overturn moves forward, and the autumn overturn moves back. As the thermal stratification of lakes continues for longer in the summer and primary production increases in water bodies, oxygen levels near the lake bed may deplete faster and anaerobic conditions prevail for longer periods of time (Kauppi & Kämäri 1996). This may harm several species and especially decomposers found in the benthic zone in lakes. Prolonged anaerobic conditions favour species that have adapted to low levels of oxygen (Tonn 1990). The common bream (Abramis brama) and the crucian carp (Carassius carassius), for example, can tolerate very low levels of oxygen (Auvinen 2008). The lack of oxygen also causes nutrients stored in the lake bed or riverbed to be released and increases internal loading and eutrophication in water bodies. Thermal stratification may nevertheless decrease in some lakes in Southern Finland, and strong winds may mix water even in the summer, therefore preventing the development of anaerobic conditions (Kauppi & Kämäri 1996).

Water levels in all water bodies are expected to vary more in the future, and periodical and local flooding is likely to increase across the country. Floods are expected to become increasingly irregular, and spring floods may decrease as winter flooding becomes more common. The risk of flooding is especially high in lakes with large drainage basins, such as Lake Saimaa and Lake Päijänne (Silander et al. 2006). During floods, surface runoff from terrestrial ecosystems increases and the capacity of water supply systems may be exceeded, which may result in wastewater being released directly into water bodies. Nutrients, solids, and harmful substances damage water quality and increase eutrophication and oxygen demand in water bodies. Flooding is associated with fish death due to the lack of oxygen.

The scale of the effects of climate change varies from one type of water body to the next. Its impact on small water bodies, such as brooks and ponds, is likely to be substantial, because changes in air temperature, for example, have a strong effect on them and because they are more sensitive to thermal stress than larger water bodies. Small brooks are sensitive to changes in surface runoff. Small ponds are susceptible to the effects of summer droughts (Heino, Virkkala & Toivonen 2009).

Increasing levels of carbon dioxide in the air and nitrogen introduced by means of surface runoff cause acidification in water bodies (Silander et al. 2006), which affects all aquatic organisms and especially invertebrate animals with calcareous shells, such as snails.

Global warming brings changes to the prevalence of species

The diversity of species in freshwater ecosystems is partially dependent on the climate, and the diversity of many groups of species decreases towards the north in the northern boreal ecoregion (Heino, Virkkala & Toivonen). Examples of this include dragonflies, fish, diatoms, and large aquatic plants (Heino 2001; Heino

& Toivonen 2008; Weckström & Korhola 2001). Increasing mean temperatures may therefore have an effect on the regional diversity of species and biological communities.

Studies indicate that the increase of spring temperatures, which began in the 1840s, has affected the composition of the biological communities found in lakes across Lapland. With global warming, the prevalence of diatom species (Bacillariophyta), in particular, has changed and diversity either decreased or remained relatively unchanged. The change is believed to be attributable to increased thermal stratification in the studied lakes, which has favoured planktic species instead of benthic ones (Sorvari, Korhola & Thompson 2002). Lake Saanajärvi also demonstrated changes in the composition of species of golden algae (Chrysophyta) and zooplankton (Korhola et al. 2002). These results can be used to project the effects of anthropogenic climate change.

Coldwater species are likely to decrease in the future and species more typically associated with warm and cool water increase and spread towards the north (Heino, Virkkala & Toivonen 2009). In terms of fish, the Arctic char (*Salvelinus alpinus*), the lavaret (*Coregonus lavaretus*), and the brown trout (*Salmo trutta*), in particular, rely on cold water and have a low tolerance to thermal stress (Auvinen 2008; Lappalainen & Lehtonen 1997). The metabolic rate of fish increases in warm water, and their ontogenesis and reproduction may accelerate. Competition between species as well as diseases and parasites may also increase (Wrona, Prowse & Reist 2004). Increasing water temperatures will be problematic especially for coldwater species in small ponds, which lack the colder deeps typical of larger water bodies where fish can escape in hot summer weather (Heino, Virkkala & Toivonen 2009).

Adaptation to changing conditions is especially important for the survival of coldwater species. This may be possible at least for species with a short generation time but may be more difficult for long-living species. Top predators in the food web tend to be long-living, and a decrease in the numbers of predator species could increase the prevalence of species on the lower levels of the food web (Wrona, Prowse & Reist 2004).

The prevalence of different species in inland waterways may also change as a result of indirect effects. The decreasing prevalence of coniferous trees and the increase of broadleaf trees, for example, is likely to affect invertebrate aquatic species, because leaves and needles falling from trees are an important source of nutrition for them. Because leaves have a higher nutritional value than needles, invertebrates would have more nutrition available to them, which could lead to changes in the prevalence of species (Heino, Virkkala & Toivonen 2009).

Ecological connectivity between habitats and the dispersal ability of species regulate changes in geographic ranges

Little research has gone into changes in inland water species so far, but, in the case of many species, changes in geographic ranges via inland waterways may be slower than those in terrestrial ecosystems. This is due to dispersal barriers between waterways. Poor connections from one habitat to another make it more difficult for populations to survive and for new species to disperse to an area. Species with the best dispersal ability have the best chances of survival. There are considerable differences between the dispersal ability of different species, and it is possible that species found in lakes and ponds have developed better dispersal strategies than species found in fluvial waters. This is why the effects of climate change on the geographic ranges of species may show more slowly in fluvial waters (Hof, Brändle & Brandl 2008). This theory does not necessarily apply to all species, and in some lakes dispersal barriers may affect the ability of coldwater species, for example, to disperse to new areas (Heino, Virkkala & Toivonen 2009). Competition between species also affects the changes in the prevalence of species in each habitat.

In addition to certain microscopic algae, dragonflies (Odonata) are also potentially good indicators of climate change, because the lack of ecological connectivity and terrestrial ecosystems are likely to restrict the dispersal of flying insects less than that of fish, for example (Heino, Virkkala & Toivonen 2009). New species of dragonflies have been spotted in Finland every year during the 2000s, and with climate change the number of species is expected to increase further (Campbell et al. 2009). Although the arrival of new species is assumed to be attributable to warm summers, no actual longitudinal studies have been carried out in Finland on the effects of climate change on the prevalence of different species of dragonflies.

Eutrophication as well as increasing rainfall and surface runoff may increase the amount of carbon released from inland waterways

Lake sediments are the third largest natural carbon store in Finland. Approximately 0.62 Pg of carbon has been sequestered in them since the last ice age. The carbon dioxide emissions of lakes have been estimated to amount to approximately 1,400 Gg per year with approximately 65 Gg of carbon sequestered in lake bed sediments annually. Studies indicate that there is a strong correlation between annual rainfall and the annual carbon dioxide emissions of lakes. This may be due to the fact that more organic matter is leached into lakes from drainage basins during years with heavy rainfall. Eutrophication in lakes also increases the volume of readily biodegradable organic matter and increases the rate of decomposition. This increases the natural carbon dioxide and methane emissions of lakes. If rainfall increases with climate change and eutrophication accelerates, carbon dioxide emissions from natural sources may also increase (Rantakari 2010).

Other changes in biodiversity

The combined effect of climate change and acidification, eutrophication, changes in land use, and the impact of alien species may have unpredictable consequences on aquatic species (Heino, Virkkala & Toinoven 2009). With climate change, the number of alien species introduced to inland waters by man is likely to increase further (Campbell et al. 2009), as conditions become more favourable to the survival of species originating from more southern areas. Alien species affect ecosystems and their native species through competition, predation, illnesses, and parasites, for example.

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3.8 Ensuring sustainable fish production in Europe under climate change: Italy, Czech Republic and Norway study cases

Climate change represents a threat for sustainable growth in aquaculture and fisheries worldwide. The world population is growing, and the demand for food is increasing. Forecasts indicate an overall decline in food production due to climate change. The ClimeFish project (2016-2020) helped ensure that the increase in seafood production comes in areas and for species where there is a potential for sustainable growth, given the expected developments in climate, thus contributing to robust employment and sustainable development of rural and coastal communities. Within the framework of ClimeFish, the growth of the most important and the less resilient cultured and wild caught fish and shellfish species in Europe was simulated during the RCP4.5 (moderate emissions) and the 8.5 (high emissions) IPCC scenarios. The project addressed three production sectors: marine aquaculture, marine fisheries and lake and pond production in a total of 16 case studies, involving more than 25 species.

Italy – Lake Garda

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One of the case studies is Lake Garda (lago di Garda), the largest Italian lake (370 km2), with a watershed of about 2300 km2. Several freshwater fish species are present in the lake, among them an important role for fishery is played by *Coregonus lavaretus*, also known as lavaret, in addition to common whitefish or European whitefish. The lake also hosts a rare endemic salmonid fish, *Salmo carpio*, also known as carpione, that has been strongly declining and is considered critically endangered (IUCN 3.1). The fishing activity is deeply rooted in the local populations residing around the lake, even if the economic importance decreased during last decades. At present commercial fishermen are about 100, whereas anglers are estimated around 2000.

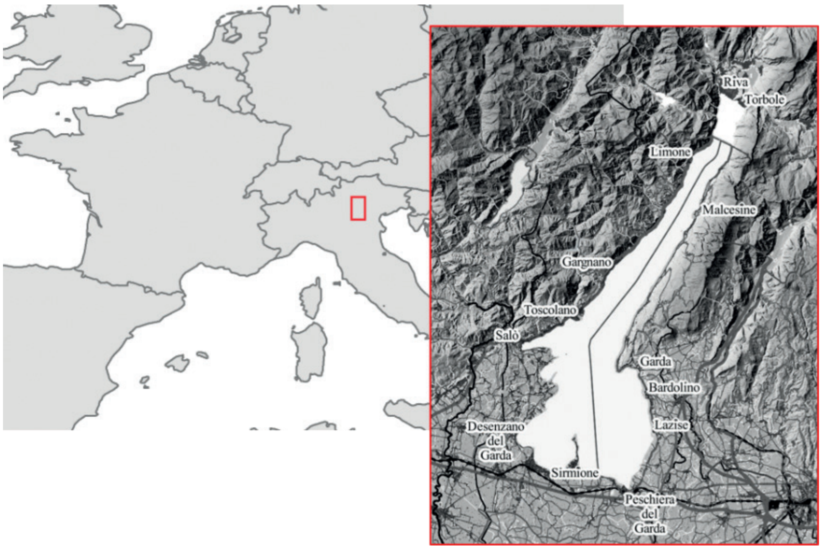

Fig. 16: Map of Lake Garda in northern Italy.

Main results of the ClimeFish assessment:

- Temperature increase in Lake Garda can exceed the optimal levels for several species, leading to decreased growth performance and biomass reduction
- The warmer waters could affect the survival of some life-stages, representing a potential criticality for recruitment
- The severity of the climate induced changes is mediated (attenuated or exacerbated) by the management of fishery

- There are relevant knowledge gaps, that should be filled to move towards a knowledge-based management
- Regular monitoring programs should be established to let the managers regulate fishery and take into account the ongoing changes in the lake.

Effects of climate change:

Air temperature change is expected to drive raise temperature in the lake Garda, affecting the growth of the species and the water circulation pattern within the basin. For the whitefish, the most important species for the commercial fishery, a moderate temperature increase could still stimulate individual growth, but severe temperature increases could deteriorate growth performance.

Risks and opportunities:

The main risks identified in ClimeFish, through interaction with stakeholders, are related to the state of the stocks. These risks include:

- Decreased natural recruitment for the whitefish
- Decreased biomass for different species
- Decreased productivity in different areas of the lake
- Emergence of invasive species
- Risks directly linked to fishing activity include longer winter closure, reduced number of issued licenses and decreased catch efficiency.

Adaptation strategies:

The adaptation strategy for the fishery in lake Garda should encompass the adaptation of actions at industry and policy level, and the closure of knowledge gaps. For industry, actions should relate to the adaptation of fishing gears and techniques to account for changed fish distribution (mainly along the depth column). Furthermore, product innovation and marketing strategies are necessary in order to enhance the valorization of the fishery products, either to increase the price or at least avoid devalorization. Regular monitoring of the biological characteristics of the lake and an observatory of the fishing activity (both professional and recreational), should constitute the base for moving toward a knowledge-based management of the resources, that appears to be even more relevant considering the potential impacts of climate change.

Socio-economic outcomes:

Predicting the climate's influence on the evolution of socio-economic aspects of fishery in the lake Garda is difficult. However, the stock size of some of the target species is expected to diminish and the lake's productivity is expected to decrease. As the relative importance of fishery in the local economy decreased in the last decades, it would be very important that a policy for the valorization of the fish products could support the sustainability of the sector, involving not only the fishery operators but also other activities, such as the tourism industry.

Lake Lipno – Czech Republic

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Warm-water predatory fish species such as European wels catfish (*Silurus glanis*) and pikeperch (*Sander lucioperca*) are highly valued in freshwater fishery in Central Europe. Lake Lipno is the largest Czech reservoir close to the Austrian border. This lake has been famous for the best pikeperch fishery in Central Europe for decades. One would expect that with increasing temperatures due to climate change, the future of Lipno pikeperch fishery is rosy. This is however in stark contrast with recent trends: Pikeperch catches in Lake Lipno collapsed spectacularly in early 2000s after more than two decades of stable or increasing catches. Local angling authorities were forced to employ protective measures to lower the fishing pressure. The changes in fish catches in the whole Czech Republic show that the case of Lake Lipno is typical of many other lakes. Lake Lipno case study can therefore support sound management decisions in many other fishing grounds.

Main results:

- The two main drivers of warm-water fish are temperature and food quantity
- New methods for calculating Eurasian perch was developed
- Carp in central Europe is still in suboptimal conditions. It does not reproduce naturally, and biomass loss exceeds the production
- IBM forecasting the biomass and yield of pikeperch was developed for the Lipno reservoir.

Effects of climate change:

Temperature, invasive species, eutrophication, and fishing are main threats to the coldwater species in central Europe, such as brown trout and whitefish. In some water systems they are already extinct. Oligotrophication (decrease in nutrients) improves water quality but decreases production of commercial species. The emerging top predator, the wels catfish, thrives with increasing water temperatures, but is a threat to many species, especially percid fish, which also experiences suboptimal temperature conditions as temperatures increase.

Risks and opportunities:

Risks: Complete loss of cold-water species, overfishing of commercial species, economic losses from intensive carp fishery. In the distant future, overbreeding of carp or some allochthonous warm water fish.

Opportunities: Increased production of emerging warm water fish (catfish, pikeperch, carp, other cyprinid fish, centrarchids). Predatory species can be exploited as new biomanipulation tools.

Adaptation strategies:

Maximum protection of cold-water fish (fishing ban and preventing invasive fish). Fishery regulations and focusing of fishermen’s attention on utilisation of emerging species. Biomeliorative measures: water level manipulation during spawning, stocking of predatory species, biomeliorative catches.

Socio-economic outcomes:

Salmonid fish will be considered luxury goods as salmonid fishery decreases in importance. This may not mean the decrease of its economic importance if people are willing to pay for luxury goods.

Also, warm water fishery has to be changed. Finding the right balance of the developing food web may be a challenge as even emerging species can be overfished. However, future challenges may lead to improving fisheries management as a whole.

North Norwegian Lakes - Norway

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Freshwater fish species adapted to cold waters are particularly vulnerable to climate warming as they experience unfavourably high temperatures in the southernmost reaches of their distributions. Salmonid species, with their narrow thermal tolerance and growth-dependent population dynamics, exemplify how climate changes may affect cold water species targeted by inland fisheries. The North Norwegian Lakes case study focuses on the salmonid species brown trout (*Salmo trutta*), Arctic char (*Salvelinus alpinus*) and whitefish (*Coregonus lavaretus*) as well as the invasive vendace (*Coregonus albula*).

Main results:

- Salmonids in Northern lakes will experience rapid and substantial warming resulting in a prolonged ice-free season and higher water temperatures
- Warmer waters at high latitudes will promote temperature-dependent growth for all investigated species
- Faster somatic growth will lead to increased biomass and production
- Inland fisheries may benefit from faster growth at moderate fishing pressures, but any benefit is lost with increasing exploitation pressure
- Younger individuals and, for late maturing species, juveniles, will be more exposed to size selective fisheries
- Warming will enhance fishing induced age-truncation and immature mortality thereby increasing the vulnerability of harvested populations

Climate warming effects:

Salmonids in Northern lakes will experience rapid and substantial warming resulting in a prolonged ice-free season and higher water temperatures. Warmer waters at high latitudes will promote temperature-dependent growth for all investigated species. When realized, faster somatic growth will lead to increased biomass and production, and potentially yield, under moderate fishing pressure.

Risk and opportunities:

Climate warming will increase the risk of overexploitation for sensitive species such as trout and Arctic charr under intense size-selective harvesting by gillnet fishery. The combination of climate warming and size-selective harvesting will enhance demographic vulnerability to natural or human induced perturbations via sharp age truncation. For moderate harvest pressures targeting narrow size ranges, the higher recruitment rates of large individuals, due to faster growth at higher temperatures, may improve conditions for recreational fisheries.

Main strategies for adaptation:

Inland fisheries in Northern Scandinavia are primarily recreational and sustenance activities exploiting many fish populations widely distributed over a large territory that is sparsely populated. Exploitation regimes and stock assessment are often left to the discretion of landowners and fishermen, as regional authorities have limited means to help monitor resources and enforce regulation. Overexploitation by gillnet fishery of large salmonids like trout and Arctic charr is common, as best practice must rely on local experience and judgment which is informed by undesired events. Further, regulation varies regionally with laissez-fair regimes or loose regulation in areas with limited scope for adaptive monitoring. To cope with the ecological change driven by climate warming, regulation should limit fishing pressure and target gillnet fishery, prescribing narrow mesh size ranges. Adaptive monitoring of selected basins and fish populations, functioning as sentinels of change, representative for relevant management areas and eco-regions, should integrate stock and ecosystem assessment best practice.

Potential socio-economic outcomes:

As inland fisheries in Northern Norway are primarily related to recreation and sustenance, the primary concern of climate driven impact on fish and fisheries will be for local landowners and fishermen. But tourism is likely to have an increasing share of the recreational fishery in the coming years, potentially increasing fishing pressure via angling in lakes and rivers, with salmonids as preferred target. Climate adaptation plans will have to take such changes in inland fisheries into account when specifying new management options.

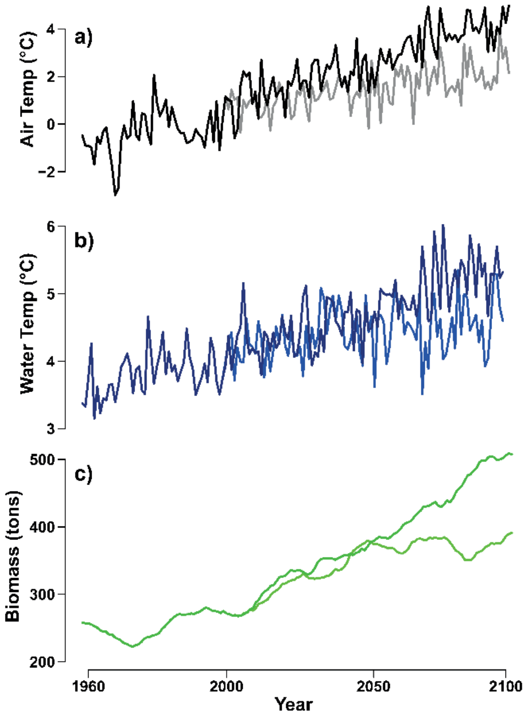

Fig. 17: Projection of a) air temperature (°C), b) water temperature (°C) and c) Arctic char biomass (tons) under the RCP-4.5 and RCP-8.5 (light and dark shades, respectively) climate scenarios from 1953 to 2100.

4. Project examples from Europe

In this chapter we introduce and highlight some successful practical EU approaches and projects for mitigation, adaptation and risk minimisation with respect to climate change impacts and risks for water ecosystems in Europe.

4.1 ESA Lakes Climate Change Initiative Project (Lakes-CCI)

Project Duration	Ongoing
Countries	France, United Kingdom, Italy, Canada, Germany, Romania, Spain, Norway
Summary	The Lakes Climate Change Initiative (Lakes-CCI) Project is part of the European Space Agency's Climate Change Initiative Programme to produce long term datasets of Essential Climate Variables (ECV's) derived from global satellite data. Lakes are of significant interest to the scientific community, local to national governments, industries and the wider public. A range of scientific disciplines including hydrology, limnology, climatology, biogeochemistry and geodesy are interested in distribution and functioning of the millions of lakes (from small ponds to inland seas), from the local to the global scale. Remote sensing provides an opportunity to extend the spatio-temporal scale of lake observation. In this context, Lakes-CCI develops products for the following five thematic climate variables: • Lake Water Level (LWL): A proxy fundamental to understand the balance between water inputs and water loss and their connection with regional and global climate changes. • Lake Water Extent (LWE): A proxy for change in glacial regions – mainly lake expansion - and drought in many arid environments, water extent relates to local climate for the cooling effect that water bodies provide. • Lake Surface Water temperature (LSWT): Correlated with regional air temperatures and a proxy for mixing regimes, driving biogeochemical cycling and seasonality. • Lake Ice Cover (LIC): Freeze-up in autumn and advancing break-up in spring are proxies for gradually changing climate patterns and seasonality. • Lake Water-Leaving Reflectance (LWLR): A direct indicator of biogeochemical processes and habitats in the visible part of the water column and an indicator of the frequency of extreme events.
Website	https://climate.esa.int/en/projects/lakes/

4.2 ESPON LAKES – Targeted territorial analysis of spatial progress and integrated development opportunities of large lakes in Europe

Project Duration	1 October 2020 to 28 February 2022
Project Budget	228.605,00 €
Countries	Germany, Hungary, Sweden
Summary	In the EU there is no specific approach developed for the integrated development for regions of large lakes, including their social-economical space and the catchment areas. Against this background, this EU funded project aimed at providing recommendations for developing effective spatial development tools for European large lakes. Analyses were mainly focusing on territorial policies and lake governance aspects, but due to the ecological dimension and environmental regulation of large lakes, the consideration of environmental conditions were also required. The project provided recommendations to practitioners on how to identify and consider the specific territorial context in lake regions for a better management and integrated development of European large lakes.
Website	https://www.espon.eu/lakes

4.3 TRIAGE – Trophic state Interactions with drivers of Aquatic greenhouse Gas Emissions

EU Grant Agreement ID	**786612**
Project Duration	1 March 2019 to 28 February 2021
Project Budget	187.419,60 €
Countries	Switzerland
Summary	In the framework of the EU-funded TRIAGE Project, ecologists investigated emissions of greenhouse gases (GHGs) from Swiss lakes and the role they play in determining productivity. The results contributed to predicting the impact of climate change on freshwater ecosystems. Lakes play important roles in global carbon cycles by receiving, transforming, storing, emitting, and transporting carbon. Carbon is being emitted as carbon dioxide (CO_2) and methane (CH_4), which are both potent GHGs. Lakes also emit nitrous oxide (N2O), another GHG. Scientists currently do not possess a detailed understanding of GHG dynamics in aquatic systems. This limits the ability to predict how these emissions will be altered in response to global environmental changes. One consequence of climate and land use change for surface waters is eutrophication, whereby water quality is degraded because of excess nutrient loading, namely phosphorus and/or nitrogen. The TRIAGE project addressed this topic by quantifying how aquatic GHG emissions vary with trophic state and by developing a model describing the main drivers of this variability. This helps to predict the response of aquatic systems to environmental change. The TRIAGE research involved surveys of seven Swiss lakes (Baldegg, Hallwil, Soppen, Bretaye, Chavonnes, Lioson and Noir) constituting a climate, size, and trophic gradient. Results indicate that the balance of GHG emissions shift with trophic state, so that more eutrophic systems emit more GHGs.
Website	https://cordis.europa.eu/article/id/430389-role-of-lakes-in-climate-change-revealed

4.4 BINGO: Bringing INnovation to onGOing water management – A better future under climate change

EU Grant/Agreement ID	**641739**
Project Duration	1 July 2015 to 30 September 2019
Project Budget	7.822.422,50 €
Countries	Cyprus, Denmark, Germany, Netherlands, Portugal, Spain
Summary	There are plenty of long-term concepts on how to face Climate Change. But how can decision-makers and end users face the intermediate challenges Climate Change brings? What is the right path and time scale to address today and be prepared to future climate scenarios? The Horizon 2020 project BINGO aimed at providing practical knowledge and tools to end users, water managers and decision and policy makers affected by Climate Change o enable them to better cope with all climate projections, including droughts and floods. Led by Laboratório Nacional de Engenharia Civil (LNEC, Portugal), the project involved 20 European Partners from six countries, including research and innovation centres, water authorities, water users and companies. BINGO provided demand-driven solutions for specific climate related challenges, in particular for highly vulnerable water resources of strategic importance. It addressed average and extreme conditions of Climate Change scenarios in six areas across Europe, from North to South. **Project outcomes of BINGO:** • Improved and downscaled climate predictions and projections of climate variables; • Integrated analysis of the impacts of Climate Change scenarios on the water cycle; • Improved dialogue between different actors, including decision makers; • Increased public awareness of the effects of Climate Change on floods and droughts; • Development of knowledge and tools for a more efficient management of water resources in Europe.
Website	www.projectbingo.eu/about-bingo

4.5 REFRESH – Adaptive Strategies to Mitigate the Impacts of Climate Change on European Freshwater Ecosystems

EU Grant Agreement ID	**244121**
Project Duration	1 February 2010 to 31 January 2014
Project Budget	9.895.943,67 €
Countries	Denmark (Sandemans baek, Voel baek), Estonia (Lake Võrtsjärv), Germany (Müggelsee), Norway (Lake Vansjø), Lake Mjøsa), Spain (Caselas and Pego), Sweden, The Netherlands (Groote Moolenbeek), Turkey, United Kingdom
Summary	REFRESH had three overarching goals; i) to increase the understanding of how freshwater ecosystems will respond to the environmental changes driven by climate, land use, water use and pollution over the next 50-60 years; ii) to translate this knowledge into a form that can be used by water managers; and iii) to ensure uptake of REFRESH results by target stakeholders. REFRESH adopted an approach to increasing understanding of how freshwater ecosystems will respond to global change drivers, how this might be managed practically and conceptually and how much management measures will cost. The project collected existing knowledge from a wide range of sources and generated new knowledge using experimental and analytical approaches. To increase the fundamental understanding of the mechanisms through which key global change-related drivers will affect freshwaters, REFRESH used a series of coordinated field experiments determining the impact of changing temperatures, changes in water flows & levels and the interaction between these as well as nutrient concentration on rivers, lakes and riparian wetlands. The ultimate objective of REFRESH was to develop integrated models to generate robust simulations of future water quantity, quality and ecology at the catchment scale. A key priority of REFRESH was to improve the ecological parts of the models and to couple existing integrated models for flow and water chemistry to ecological models of appropriate complexity. To assess the implications of model output for management, REFRESH identified the most cost-effective ways of mitigating the adverse impacts of climate change and the impacts of these on achieving good ecological status under the WFD.
Website	https://cordis.europa.eu/project/id/244121

4.6 EULAKES – European Lakes Under Environmental Stressors: Supporting lake governance to mitigate the impact of climate change

Project Duration	1 April 2010 to 31 March 2013
Project Budget	2.910.799,00 €
Countries	Austria, Hungary, Italy, Poland
Summary	Most Central European Lakes became more valuable in view on their role as natural resources linked to regional sustainable development. Change in water temperature, regional water shortages or uneven temporal distribution of freshwater sources caused by climate change, provided initial future warning signs. The project EULAKES promoted an integrated approach in order to improve the sustainable management of Central European lakes. EULAKES combined vulnerability and risk assessment, monitoring and environmental governance. The project enhanced participative planning and management of lake basins in order to respond to climate change and other environmental stress factors. Four Central European lakes with different characteristics have been involved in the project. Lake Garda (Italy), Lake Balaton (Hungary), Lake Neusiedl (Austria) and Lake Charzykowskie (Poland). All of them provide habitats for indigenous wildlife, drinking water and a high recreational capacity. However, all four lakes are showing increasingly a growing vulnerability in their functionality. The impacts of climate change are generating new scenarios that the project intended to investigate in order to support the local governance to take future sustainable decision for the future of basin development fostering an integrated approach between researchers and local communities. At Lake Neusiedl, a pilot study assessed benefits of an agricultural and environmental management plan based on the conservation of target species. The Polish analysis of sludge and heavy metals was progressed. At Lake Balaton, ecological impacts of alien fish species have been investigated to provide answers for management

	practices of these invasive species. At Lake Garda a survey on toxic cyanobacteria provided information for the risk assessment and mitigation measures in order to avoid risks for human and ecosystem health. Dissemination of results has been realised on scientific and public level, including local authorities, stakeholders, schools and citizens.
Website	https://keep.eu/projects/5508/European-Lakes-Under-Environ-EN/

4.7 WISER – Water bodies in Europe: Integrative Systems to assess Ecological status and Recovery

EU Grant Agreement ID	**226273**
Project Duration	1 February 2009 to 28 February 2012
Project Budget	9.022.000,00 €
Countries	Austria, Bulgaria, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Netherlands, Norway, Poland, Portugal, Spain, Sweden, United Kingdom
Summary	Within the WISER project, 25 European research institutions representing 16 countries have addressed the assessment and management of rivers, lakes, transitional and coastal waters in Europe. The majority of European lakes, rivers and coastal ecosystems are degraded. Eutrophication, organic pollution, intense catchment land use and habitat degradation affect almost all European surface waters. Ecosystem functions have been lost, and many aquatic species have disappeared from entire ecoregions. Recent European policies target a good ecological status of lakes, rivers and coastal ecosystems. To achieve this, water bodies need to be assessed by comparison with a quality target and, if the quality is below the target, to be restored. For many aquatic ecosystem types ecological assessment systems have been developed; river basin management plans outline the required restoration measures.
Website	http://www.wiser.eu/

4.8 CLIME – Climate and lake impacts in Europe

EU Grant Agreement ID	**EVK1-CT-2002-00121**
Project Duration	1 January 2003 to 3 December 2005
Project Budget	5.185.757,00 €
Countries	United Kingdom
Summary	The CLIME Project has brought together a consortium of scientists and stakeholders from ten countries aiming at assessing direct and indirect effects of changes in weather and climate on lakes in Europe. Particular emphasis has been put on water quality variables as diagnosis elements for the EU Water Framework Directive (WFD). One objective was to identify models for changes in weather validated by historical data and perturbed by simulations of future variations in weather. One main output was a Decision Support System that can be used to optimise the management of lakes in increasingly warmer climates in Europe.
Main Publications	A CLIME book is available from Springer: The Impact of Climate Change on European Lakes, Series: Aquatic Ecology Series, Vol. 4 George, Glen (Ed.) 2010, XXVI, 507 p., Hardcover ISBN: 978-90-481-2944-7
Website	https://cordis.europa.eu/project/id/EVK1-CT-2002-00121

4.9 MAR2PROTECT – Protecting groundwater from climate and global change effects

EU Grant Agreement ID	**101082048**
Project Duration	1 December 2022 to 30 November 2026
Project Budget	4.143.681,25 €
Countries	Italy, Lithuania, Netherlands, South Africa, Portugal, Spain, Tunisia
Summary	MAR2PROTECT will provide a holistic approach to prevent groundwater contamination from the impacts of climate change and global change, through different innovative technologies. The main idea consists in a tool supported by Artificial Intelligence that will receive real-time information from sensors placed in risk locations where the technologies will be implemented, among other vitally important information (innovative technologies, preferences of social agents, risk assessment). The tool will allow a new generation of Managed Aquifer Recharge approach to improve groundwater quality and quantity. The core of the innovative Managed Aquifer Recharge is the M-AI-R Decision Support System which will incorporate technological and societal engagement information using an Artificial Intelligence-based evaluation to improve groundwater quality and quantity. The consortium consist of 9 partners from 6 different European-countries and 2 international partners (Tunisia, South Africa).
Website	https://mar2protect.eu/

5. Financial resources for measures such as climate change adaptation, restoration and increase of resilience in Europe

In this chapter we provide an overview of possible funding sources for projects related to climate change adaptation and mitigation as well as ecosystem restoration in Europe.

5.1 Decade of restoration of ecosystems

On 22 June 2022, the European Commission adopted the proposal for a Nature Restoration Law. This is an important step to restoring damaged EU ecosystems from wetlands, rivers, forests, grasslands, and marine ecosystems to urban environments and bringing nature back across Europe. Under this proposal for a Nature Restoration Law, legally binding targets for nature restoration in different ecosystems will apply to every Member State, complementing existing laws. The aim is to cover at least 20% of the EU's land and sea areas by 2030 with nature restoration measures, and eventually extend these to all ecosystems in need of restoration by 2050. The law will scale up existing experiences of nature restoration measures such as rewilding, returning trees, greening cities and infrastructure, or removing pollution to allow nature to recover. Ecosystems with the greatest potential for removing and storing carbon and preventing or reducing the impact of natural disasters such as floods will be the top priorities.

EU Financial support for rivers and wetlands

The EU Commission adopted the Multiannual Financial Framework (MMF) for the period 2021-2027. Projects to restore river and wetland ecosystems and to implement nature-based solutions (such as constructed wetlands) can make European regions greener and more climate resilient. As such, they will certainly be well-placed to attract EU investments in the current programming period. Based on the latest initiatives adopted by the Commission it is fair to say that the outlook is rather positive for policymakers who intend to turn rivers and wetlands into drivers of regional sustainable development.

With the 2030 EU Biodiversity Strategy, the EU executive has indeed clarified that reversing biodiversity loss and restoring ecosystems - including those of rivers and wetlands - will require 'making the most of all EU relevant programmes and funding instruments' including the CAP, European Structural and Investment Funds, Horizon Europe and the LIFE programme. Resources flowing from these programmes and instruments need to be matched by significant public and private investments at national and regional levels since the challenge of implementing the Strategy is a great one and requires a yearly expenditure on nature of 20 billion EUR. According to the Commission also InvestEU sustains efforts in this direction through a dedicated natural-capital/circular-economy initiative that will mobilise at least 10 billion EUR in the next decade based on public/private blended finance.

The Farm to Fork Strategy indicated that the European Regional Development Fund (ERDF) is the main instrument for supporting regions in making food value chains more sustainable (which includes decreasing pressures on water resources) and that Horizon Europe (with 10 billion EUR) will support research and development on food (including fisheries and aquaculture) and the environment (e.g. to foster nature-based solutions for agri-food). The so-called 'eco-schemes' of the post 2020 CAP are expected to offer a stream of funding to boost sustainable practices. The goal of increasing substantially organic aquaculture by 2030 set by the Action Plan for organic production is supported by the European Maritime, Fisheries and Aquaculture Fund (EMFAF).

To achieve the target set by Smart and Sustainable Mobility Strategy of increasing multimodal transport and the share of waterborne transport on inland waterways regions will continue to make use of ESIFs and, for cross-border initiatives, the Connecting Europe Facility (CEF), which will still be the 'main instrument to finance infrastructure development with maximum EU-added value, while mainstreaming the green and digital objectives'. Moreover, the mission area on 'Climate neutral and smart Cities' under Horizon Europe could help cities to find innovative solutions for cycling along rivers and deploying zero emission solutions for both freight and passenger transport on inland waterways to achieve one of the milestones outlined in the Strategy, namely, having at least 100 completely decarbonised cities by 2030.

The local and regional implementation of the new EU Strategy on Adaptation to Climate Change will count on the increased spending target of 30% for climate action in the long-term EU budget for 2021-2027. Resources for adaptation will be primarily made available under the Cohesion Fund and the ERDF, inter alia to promote nature-based solutions that will reinforce green-blue infrastructures, thereby building climate resilience and reaching socio-economic goals. Additionally, also the LIFE programme and the future CAP are set to contribute to ensuring the availability and sustainability of freshwater and the roll-out of nature-based solutions for maintaining healthy rivers and wetlands. Furthermore, the Strategy emphasises the need to leverage long-term investments in nature-based solutions, hints to the role that may be played in this respect by InvestEU, and the new climate roadmap of the European Investment Bank. Finally, with its mission areas on 'Adaptation to Climate Change, including Societal Transformation' and 'Healthy oceans, seas, coastal and inland waters', Horizon Europe is also expected to give great support to innovative climate adaptation solutions involving rivers and wetlands.

Source: EU Policy Brief on Rivers and Wetlands https://www.interregeurope.eu/find-policy-solutions/policy-briefs/rivers-and-wetlands-drivers-of-sustainable-regional-development

5.2 EU LIFE Programme

EU LIFE Circular Economy and Quality of Life Call 2023

Main objectives	Supporting the transition to a circular economy and protecting and improving the quality of EU's natural resources, including air, soil and water among others.
Specific objectives	The specific objective is to cover one or more of the following topics: 1. Circular Economy and Waste 2. Air 3. Water 4. Soil 5. Noise 6. Chemicals 7. A new European Bauhaus The specific objectives of the sub-programme 'Circular Economy and Quality of Life' are: - to develop, demonstrate and promote innovative techniques, methods and approaches for reaching the objectives of the EU legislation and policy on environment, and to contribute to the knowledge base and, where relevant, to the application of best practices - to support the development, implementation, monitoring and enforcement of the EU legislation and policy on environment, including by improving governance at all levels, in particular through enhancing capacities of public and private actors and the involvement of civil society - to catalyse the large-scale deployment of successful technical and policy-related solutions for implementing the EU legislation and policy on environment, by replicating results, integrating related objectives into other policies and into public and private sector practices, mobilising investment and improving access to finance. This sub-programme aims at facilitating the transition toward a sustainable, circular, toxic-free, energy-efficient and climate-resilient economy and at protecting, restoring and improving the quality of the environment. It will contribute to the EU priorities by: - reducing resource consumption and facilitating the transition toward a sustainable, circular, toxic-free, energy-efficient and climate-resilient economy - developing circular systems, in line with the new Circular Economy Action Plan and reflecting its focus on sustainable products, material and energy intensive sectors and circular business models for value retention - bringing down waste generation in line with the Waste Framework Directive 2019/1004Basel Convention5. 4 and the reduction of hazardous waste in view of the EU's commitment under the improving waste management with respect to collection and storage of waste, recovery options and end-of-life disposal, including in islands where waste management has to face specific challenges - reducing emissions of pollutants to air and ensuring clean air for EU citizens in line with the EU legislation and the objectives of the Zero Pollution Action Plan - achieving and maintaining a good status of the EU water bodies - ensuring clean surface water and ground-water, in sufficient quantities for human and other species, including by increasing efficiency of water use - reducing production, use and emissions of hazardous chemicals as well as reducing the exposure of humans and the environment to those chemicals

	- promoting the development, commercialisation and uptake of safe and sustainable-by-design substances, materials and products - diminishing exposure to harmful noise levels - protecting the quality of EU soil, preventing soil degradation through sustainable practices of soil and land management, remediating from soil pollution and enhancing the capacity to improve water quality through reduced nitrate leakage and to reduce emissions through carbon storage.
Deadline	6th of September 2023
Expected effects	a) Contribute to the development of new or existing national legislation, policies, regulations, incentives and voluntary commitments b) Achieve a step-change in more effective compliance with and enforcement of Union environmental and climate legislation and/or in policy implementation c) Achieve a step-change in awareness and support of environmental and climate matters d) Establish a new macroregional or national model of cooperation (networking)
Eligible applicants	In order to be eligible, the applicants (beneficiaries and affiliated entities) must: – be legal entities (public or private bodies) – be established in one of the eligible countries, i.e.: – EU Member States (including overseas countries and territories (OCTs)) – non-EU countries: – listed EEA countries and countries associated to the LIFE Programme (associated countries) or countries which are in ongoing negotiations for an association agreement and where the agreement enters into force before grant signature (list of participating countries)10
Funding rate	60 % EU LIFE funding. All other funding sources are allowed, except other EU Programmes.

EU LIFE Nature & Biodiversity - Standard Action Projects (SAP) Call 2023

Main objectives	Projects should fall under at least one of the two areas of intervention: - Intervention area: "Space for Nature" Any project aimed at improving the condition of species or habitats through area-based conservation or restoration measures falls within the eligible scope of the intervention area "Space for Nature". This may include, for example, projects for restoring or improving natural or semi-natural habitats, or habitats of species, both within and outside existing protected areas. This may also include projects for creating additional protected areas (or improving the biodiversity focus and contribution of existing protected areas), ecological corridors or other green infrastructure, projects testing or demonstrating new site management approaches, projects acting on pressures, etc. - Intervention area: "Safeguarding our species" Any project aimed at improving the condition of species (or, in the case of invasive alien species, reducing their impact) through any relevant activities other than area-based conservation or restoration measures falls within the scope of the intervention area "Safeguarding our species". Considering the broad range of threats that may act on species in addition to the degradation of their habitats, such projects may apply to a wide range of relevant measures, spanning from hard infrastructural works to awareness raising of stakeholders. **Nature Governance:** LIFE-2023-SAP-NAT-GOV — Nature Governance **Objectives** Proposals under this topic must support the implementation of the governance aspects (i.e. compliance assurance, public participation, access to justice) of the EU Biodiversity Strategy for 2030, with a focus on EU Nature and Biodiversity legislation by:

	- promoting effective public participation and access to justice in nature and biodiversity policy and legislation-related matters amongst the public, NGOs, lawyers, the judiciary, public administrations; and/or - establishing new or, where in place, enhancing existing cross-border, national or regional networks of compliance assurance practitioners or experts; and/or - establishing or, where in place, improving professional qualifications and training to improve public participation, access to justice and compliance with binding EU legal instruments on nature and biodiversity, through promoting, checking and enforcing compliance; and/or - developing and implementing strategies and policies and/or developing and using innovative tools and actions to promote, monitor and enforce compliance with binding EU instruments on nature and biodiversity, including use of administrative law, criminal law and environmental liability; and/or - improving relevant information systems operated by public authorities; and/or - engaging with citizens and others to promote and monitor compliance, and ensure application of environmental liability in relation to EU nature and biodiversity legislation.
Budget	EUR 145.000.000
Funding	60 % EU LIFE funding. All other funding sources are allowed, except other EU Programmes.
Deadline	6th of September 2023

EU LIFE Climate Change Mitigation and Adaptation Call 2023

Main objectives	Supporting implementation of the 2030 energy and climate policy framework, the EU's climate neutrality objective by 2050, and the new EU strategy on adaptation to climate change. The call covers the following topics: - LIFE-2023-SAP-CLIMA-CCM - Climate Change Mitigation - LIFE-2023-SAP-CLIMA-CCA - Climate Change Adaptation - LIFE-2023-SAP-CLIMA-GOV - Climate Governance and Information The specific objectives of the sub-programme 'Climate Change Mitigation and Adaptation' are: - to develop, demonstrate and promote innovative techniques, methods and approaches for reaching the objectives of the EU legislation and policy on climate action and to contribute to the knowledge base and to the application of best practice - to support the development, implementation, monitoring and enforcement of the EU legislation and policy on climate action, including by improving governance at all levels, in particular through enhancing capacities of public and private actors and the involvement of civil society - to catalyse the large-scale deployment of successful technical and policy-related solutions for implementing the EU legislation and policy on climate action by replicating results, integrating related objectives into other policies and into public and private sector practices, mobilising investment and improving access to finance. This sub-programme will contribute to the transformation of the EU into a climate-neutral and -resilient society, by supporting the implementation of the EU's climate policy and preparing the EU for the climate action challenges in the coming years and decades.

Specific objectives Climate Change Mitigation	Projects under the Climate Change Mitigation Priority Area should contribute to the socially just and sustainable transition towards a climate neutral economy by 2050 and to reaching the EU emission reduction target for 2030 of at least 55% compared with 1990 levels. Union climate policy and legislation to reduce greenhouse gas emissions focuses in particular on: • sustainable renewable energy, • energy efficiency, • the emissions trading system, • energy and greenhouse gas intensive industrial production, • land use, agriculture and forestry, • increase of carbon sequestration in ecosystems, • zero and near-zero emission transport solutions and fuel/energy options, • fluorinated gases and ozone depleting substances, • carbon capture and use; as well as carbon capture and storage, • greenhouse gas monitoring and reporting, • efforts by all sectors of society and economy to reduce greenhouse gas emissions, including public bodies (national, regional and local authorities); private commercial entities; or non-commercial organisations (unions, civil society organisations, educational institutions, consumer groups), and • behavioural change, also through activities of the European Climate Pact.
Specific objectives Climate Change Adaptation	More specifically, projects under this call should support the strat-egy's objective to: • **make adaptation smarter** (improving knowledge, managing uncertainty, and informing adaptation actions by robust data and risk assessment tools that are available to all); • **make adaptation more systemic** (incorporating climate resilience considerations in all relevant policy fields, because climate change has impacts at all levels of society and across all sectors of the economy); • **make adaptation faster** (developing and rolling out adaptation solutions that allow us to adapt more quickly and comprehensivly). Furthermore, projects should take care to **avoid maladaptation**, i.e. adaptation actions or practices aimed at a group of people and that actually make them more vulnerable to climate change. In order to contribute to these objectives, projects should demon-strate a **clear and convincing intervention logic** which details: • the specific **climate risks and vulnerabilities** to be addressed; • the **suitability of the proposed adaptation options and methods** to minimise the identified risks and vulnerabilities; • the **implementation** of these options and methods **during the duration of the projec**t, and • the approach for **monitoring and evaluating** the results, includ-ing after the duration of the project. **Areas of intervention:** 1. Adaptation policy development, and adaptation strategies and plans 2. State-of-the art tools and solutions for adaptation 3. Nature-based solutions in the management of land, forests, coasts and marine areas 4. Adapting cities and regions to climate change 5. Climate-proofing and resilience of infrastructure and buildings 6. Adaptation solutions for farmers, forest managers, Natura 2000 managers and other land managers 7. Water management 8. Preparedness for extreme weather events 9. Financial instruments, innovative solutions and public private collaboration on insurance and loss data
Call	2023
Deadline	21st of September 2023

5.3 Interreg Programmes

Interreg is one of the two goals of the EU Cohesion Policy in the 2014-2020 period and it is funded by the European Regional Development Fund (ERDF). It has a budget of EUR 10.1 billion invested in the several cooperation programmes responsible for managing project funding. Interreg has three types of programmes:

- Cross border (60 programmes)
- Transnational (15 programmes)
- Interregional (Interreg C= 4 programmes: ESPON, Interact, Interreg Europe, UR-BACT)

EU Interreg Europe

Main objectives	The Interreg Europe programme, financed by the Cohesion policy's European Regional Development Fund (ERDF), was designed to support interregional learning among policy relevant organisations across Europe. The programme's objective is to enable public authorities and other relevant organisations to actively learn from the experience of other regions. This is a learning process which involves identifying, analysing, and transferring good practices with the aim of improving regional development policy instruments and ultimately delivering solutions that benefit all citizens.
Specific objectives	Greener Europe - Specific objectives: 1. Energy efficiency and reduction of greenhouse emissions 2. Renewable energy 3. Smart energy systems, grids and storage 4. Climate change adaptation, disaster risk prevention, resilience 5. Access to water and sustainable water management 6. Circular and resource efficient economy 7. Protection and preservation of nature and biodiversity, green infrastructures, pollution reduction 8. Sustainable urban mobility for zero carbon economy
Budget	The Interreg Europe programme has an ERDF budget of EUR 379 million for the 2021-2027 period.
Actions /measures financed	The programme finances two complementary types of strategic action: a) **Interregional cooperation projects**: are partnerships made up of policy-relevant organisations from different countries in Europe which work together for 4 years to exchange experience on a particular regional development issue. In the fourth and final year of implementation, the partner regions mainly focus on monitoring their project's results and impact. Calls for project proposals will be launched throughout the programming period. b) **A Policy Learning Platform**: provides a space for continuous or on demand learning where any policy-relevant organisation1 dealing with regional development policies in Europe can find solutions and request expert support to improve its policies.
Eligible for funding	Interreg Europe covers all the 27 EU Member States plus Norway and Switzerland. Organisations from all these countries, regardless of their location, are eligible to participate in this interregional cooperation programme. Organisations relevant to regional development policies and based in the 27 EU Member States, as well as in Norway and Switzerland, are eligible for Interreg Europe funding. These include: - National, regional, or local public authorities - Institutions governed by public law (e.g., regional development agencies, business support organisations, universities) - Private non-profit bodies.

Co-Financing	Public bodies and bodies governed by public law from all 27 EU member states = 80 % ERDF Private non-profit bodies from all 27 EU member states = 70 % ERDF
Next call for proposals	The second call is open on **15 March 2023** and close on **9 June 2023** at **12:00 p.m.** (midday) **CEST** (Paris time). **Call for interregional cooperation projects**: These projects gather policy-relevant organisations from different countries in Europe working together on a common regional development issue. The first three years of the projects ('core phase') are dedicated to exchange and transfer of experience among the participating partners in order to improve the policy instruments addressed by the project. In the fourth and last year ('follow-up phase'), the regions mainly focus on monitoring the results and impact of the cooperation.
More Information	https://www.interregeurope.eu/find-policy-solutions/policy-briefs/rivers-and-wetlands-drivers-of-sustainable-regional-development

EU Interreg Baltic Sea Region

Main objectives	• A smarter Europe: Innovative and smart economic transformation (enhancing research and innovation capacities, uptake of advanced technologies) • A greener, low carbon Europe: Access to water and sustainable water management, Energy efficiency; Circular economy; Urban mobility • A better cooperation governance: Enhance institutional capacity of public authorities; Other actions to support better cooperation governance
Specific objectives	Within others: A Greener Low Carbon Europe RSO 2.5 Promoting access to water and sustainable water management Sustainable waters: - Increase of the capacity to manage water and connected sectors in a more competent, sustainable and efficient way in a changing climate. - Wider application of available and newly tested water management solutions or solutions across different sectors. - Lower water pollution, removing pollutants from water and improving water quality. -- Improved urban and rural planning processes for better water management and help adapt water management strategies and action plans to emerging challenges. - Shift of consumers and production patterns in using water and materials thus preventing water pollution.
Actions /measures financed	Core projects: Duration 36 months, no budget limitation, at least 3 organisations from three programme countries; Standard type of projects including piloting Small projects: Duration 24 months; Budget up to 500.000ź; at least 3 organisations from three programme countries; Simplified project model for easy access for newcomers. Project Platforms: Duration up to 36 months; Budget defined in the call; At least three organisations from three Programme countries that are partners from Programme projects + projects of another EU funding programme; Synthesis of project results of the Programme and other EU funding programmes in one thematic field, transferring these results to target groups. **Small projects** are aimed at facilitating easier access to the Programme, in particular for those partners that have not previously participated in the Programme. Applying for a small project and implementing a small project is much simpler when compared to the core projects. For example, the budget of a small project is smaller than of a core project. The work plan consists of one work package (WP) and it may be implemented by small partnerships. In small projects, partners are encouraged to develop **practical and durable outputs and solutions** for challenges in the region. These challenges need to correspond to one of the Programme objectives. Small projects should **increase capacity of the target groups** to deal with the identified challenges during and after the end of the project implementation.

Eligible for funding	Denmark, Estonia, Finland, Latvia, Lithuania, Poland, Sweden, Germany (Nuts 3 level); Norway (Nuts 3 level). Public and private legal entities.
Co-Financing	Partners from Denmark, Finland, Germany, Sweden, Estonia, Latvia, Lithuania and Poland are entitled to receive up to 80% ERDF co-financing. Partners from Norway will receive up to 50% co-financing from Norwegian national funding.
Next call for proposals	No call announced
More Information	https://interreg.eu/programme/interreg-baltic-sea-region/

EU Interreg Central Europe

Main objectives	Cooperation for a smarter Central Europe: Projects that enhance innovation capacities and encourage the uptake of advanced technologies. But also those that build capacities for smart specialisation, industrial transition and entrepreneurship. Cooperation for a greener Central Europe: Projects that address environmental challenges in central Europe and help increasing energy efficiency and the use of renewable energy. But also those that encourage sustainable urban mobility Cooperating for a better connected Central Europe: Projects that improve transport connections of rural and peripheral regions in central Europe and enhance sustainable, intelligent and intermodal transport, including connections to TEN-T corridors. Improving governance for better cooperation in Central Europe: Projects that improve capacities of public authorities on all territorial levels for setting up and implementing integrated territorial
Specific objectives related to climate and/or biodiversity	• RSO 2.4 Promoting climate change adaptation and disaster risk prevention and resilience, taking into account eco-system based approaches • RSO 2.5 Promoting access to water and sustainable water management • RSO 2.6 Circular economy • RSO 2.7 Biodiversity and green infrastructure
Actions/measures financed	• RSO 2.4 Promoting climate change adaptation and disaster risk prevention and resilience, taking into account eco-system based approaches • RSO 2.5 Promoting access to water and sustainable water management • RSO 2.6 Circular economy • RSO 2.7 Biodiversity and green infrastructure
Eligible for funding	Austria, Croatia, Czech Republic, Hungary, Poland, Slovakia, Slovenia, Germany (Nuts 3 level), Italy (Nuts 3 level)
Co-Financing	Up to 80% ERDF co-financing.
Next call for proposals	Continuous project calls open: INTERREG Bavaria – Czech Republic https://interreg.eu/call-for-project/call-for-projects/ Call for small project fund management: INTERREG Bavaria – Czech Republic
More Information	https://interreg.eu/programme/interreg-central-europe/

EU Interreg Euro-Med

Main objectives	- A smarter Europe: - RSO 1.1 Developing and enhancing research and innovation capacities and the uptake of advanced technologies - A greener, low carbon Europe: - RSO 2.6 Circular economy - RSO 2.4 Promoting climate change adaptation and disaster risk prevention and resilience, taking into account eco-system based approaches - RSO 2.7 Biodiversity and green infrastructure - A better cooperation governance: - RSO 6.6 Other actions to support better cooperation governance
Specific objectives on climate and/or biodiversity	Policy objective 2: 2.7 enhancing protection and conservation of nature, biodiversity and green infrastructure, including in urban areas, and reducing all forms of pollution RSO 2.4 Promoting climate change adaptation and disaster risk prevention and resilience, taking into account eco-system based approaches • Improve prevention and management of natural disaster risks and risks linked to human activities. • Support public authorities in their efforts to reach 2030 and 2050 energy goals and carbon neutrality, achieving effective planning and financing for climate change adaptation and energy transition. • Foster adaptation and resilience to climate change for more sustainable living areas increasing citizens engagement. • RSO 2.7 Biodiversity and green infrastructure • Improve the sustainable management of natural resources. • Consolidate the connection of natural ecosystems at transnational level, ensuring ecological corridors to boost and preserve biodiversity. • Enhance the sustainability and resilience of natural habitats, ensuring restoration of natural functions. • Improve implementation and enforcement of environmental policies/legislations, ensuring the links between environmental protection, sustainable development and citizens health.
Actions /measures financed	Within others: **MISSION 1: STRENGTHENING AN INNOVATIVE SUSTAINABLE ECONOMY** Research and innovation, developing strategies and implementing systemic changes that cut across different sectors (for instance agriculture, fisheries and aquaculture, food, manufacturing, tourism), is essential for managing natural resources but as well technological solutions sustainably, especially in the current context of increased environmental pressure and biodiversity loss. **MISSION 2: PROTECTING, RESTORING AND VALORISING THE NATURAL ENVIRONMENT AND HERITAGE** Preservation and restoration of ecosystems and biodiversity is essential for human life. Nature contributes to a more healthy and resilient society. The preservation of ecosystems allows to mitigate natural disaster, diseases, boost resilience and regulate climate, thus reducing risks to human societies. In this perspective, the purpose of the Programme, is to continue to fight against the loss of biodiversity while boosting actions of adaption to/ mitigation of climate change impacts.
Eligible for funding	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Greece, North Macedonia, Malta, Montenegro, Slovenia, Nuts 3 level: France, Italy, Portugal, Spain. Lead partner must be a public body! Eligible partners shall be the following: 1. National, regional and local public bodies (including EGTCs as defined in Article 2(16) of Regulation (EU) No 1302/2013) 2. Public equivalent bodies: • are established for the specific purpose of meeting needs in the general interest, not having an industrial or commercial character; • have a legal personality;

	• are financed, for the most part, by the State, regional or local authorities, or by other bodies governed by public law; or are subject to management supervision by those authorities or bodies; or have an administrative, managerial or supervisory board, more than half of whose members are appointed by the State, regional or local authorities, or by other bodies governed by public law. 3. Private institutions, including private companies: • have a legal personality; • are not financed, for the most part, by the state, regional or local authorities, or other bodies governed by public law; or are not subject to management supervision by those bodies; or not having an administrative, managerial or • supervisory board, more than half of whose members are appointed by the State, regional or local authorities, or by other bodies governed by public law. International organisations, acting under national law of an EU Member State or under international law cannot act as LP; they can participate in projects only upon their explicit acceptance of all requirements deriving from the Treaty on the Functioning of the European Union and the regulations applicable in the framework of the Interreg Euro-MED Programme.
Co-Financing	80% of the total eligible budget of the project; the remaining 20% of the budget is therefore borne by the partners who must ensure the co-financing of their activities by other sources of funding (own funds, private funds or national public funds).
Next call for proposals	**5th call**: Thematic Projects: 2nd Semester 2024
More Information	https://interreg-euro-med.eu/en/documents-tools/

EU Interreg Cross-Border Programmes

Main objectives	Currently there are 60 cross-border programmes. The list of regions involved in these Interreg A Programmes - see: https://interreg.eu/strand-of-cooperation/interreg-a-cross-border-cooperation/ For each of the programmes specific priorities are defined within the common headlines: • A smarter Europe • A greener, low carbon Europe • A better cooperation governance
Relation to wetland /restoration / Climate Change	Example: Interreg Alpenrhein – Bodensee - Hochrhein RSO 2.4 Promoting climate change adaptation and disaster risk prevention and resilience, taking into account eco-system based approaches • Supported projects should aim to take proactive measures to address climate change and its consequences. It also seeks to support existing cross-border cooperation on risk management in the program area, including cooperation between police and judicial authorities in Germany, Switzerland and Austria, as well as bilateral agreements on disaster control and their implementation at the regional and local levels. RSO 2.7 Biodiversity and green infrastructure • The aim is for the funded projects to protect biodiversity, specifically the diversity of species, and to connect habitats that are important for many animals across borders. A successful project called „Reconnection on the High Rhine“ has already been completed and a second project called „Cross-Border Biotope Network on the High Rhine“ is being planned. The co-funded project should maintain the unique plants and animals, conserve existing natural areas, and support small and medium-sized companies in becoming more environmentally friendly.
Actions /measures financed	Depending on the individual programmes
Eligible for funding	Public organisations and private organisation
Co-Financing	Mainly 60 % of co-financing. For special projects up to 70 %.
Next call for proposals	Depending on the programme.
More Information	https://interreg.eu/strand-of-cooperation/interreg-a-cross-border-cooperation/

5.4 Horizon Programme

Water4All

The Water4All Partnership, cofunded by the European Union within the frame of the Horizon Europe programme, aims at enabling water security for all in the long term through boosting systemic transformations and changes across the entire research – water innovation pipeline, fostering the matchmaking between problem owners and solution providers.

Water4All brings together a wide and cohesive group of 81 partners from 31 countries in the European Union and beyond. This consortium gathers a variety of partners from the whole water Research, Development and Innovation (RDI) chain, including:

- thematic authorities in charge of water issues and policy-makers,
- local authorities,
- associations and networks representing the economic sector in the field of water at the European, national or regional level,
- research organisations.
- This consortium works together from 1st of June 2022 to June 2032.
- Water4All runs its activities across 7 themes of its strategic agenda:
- water for circular economy
- water for ecosystems and biodiversity
- sustainable water management
- water and health
- water infrastructure
- international cooperation
- water governance

The call in 2022 was on “Management of water resources: resilience, adaptation and mitigation to hydroclimatic extreme events and management tools”.

Horizon Europe: Work-Programme 2023 – 2024

Horizon Europe: 8 - Climate, Energy and Mobility

Main objectives	The overarching driver for this cluster is to accelerate the twin green and digital transitions and associated transformation of our economy, industry and society with a view to achieving climate neutrality in Europe by 2050. This encompasses the transition to greenhouse gas neutrality of the energy and mobility sectors by 2050 at the latest (as well as that of other sectors not covered by this cluster), while boosting their competitiveness, resilience, and utility for citizens and society. Europe has been at the forefront of climate science and is committed to keep delivering the knowledge for enabling efficient pathways and just transitions to climate neutrality.
Relation to wetlands/restoration / climate change	B. **Restoring Europe's ecosystems and biodiversity, and managing sustainably natural resources** to ensure food security and a clean and healthy environment;
Actions/measures financed	Activities in this work programme will contribute to all **Key Strategic Orientations (KSOs)** of the Strategic Plan (KSO C being the one with the most direct contribution): A. **Promoting an open strategic autonomy13 by leading the development of key digital and, enabling and emerging technologies, sectors and value chains** to accelerate and steer the digital and green transitions through human-centred technologies and innovations; B. **Restoring Europe's ecosystems and biodiversity, and managing sustainably natural resources** to ensure food security and a clean and healthy environment; C. **Making Europe the first digitally enabled circular, climate-neutral and sustainable economy** through the transformation of its mobility, energy, construction and production systems; D. **Creating a more resilient, inclusive and democratic European society**, prepared and responsive to threats and disasters, addressing inequalities and providing high-quality health care, and empowering all citizens to act in the green and digital transitions.
Eligible for funding	Public and private organisations. Lead partner must be a scientific institution.
Co-Financing	For scientific institutions 100 %. For NGOs 90 % on average
More Information	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/how-to-participate/reference-documents;programCode=HORIZON

Horizon Europe: 9 - Food, Bioeconomy, Natural Resources, Agriculture and Environment

Main objectives	**Destination - Biodiversity and ecosystem services** The biodiversity and ecosystem services destination of the 2023-2024 Cluster 6 work programme will support R&I for the EU environment and biodiversity protection framework and the European Green Deal. It is based on the vision developed in the EU biodiversity strategy for 2030 and will support its implementation, furthering the orientations of the 2021-2022 work programme. It will also take into account new European Green Deal initiatives, notably i) the EU forest strategy for 203018, ii) the EU action plan: "towards zero pollution for air, water and soil", iii) the EU climate adaptation strategy and iv) the EU soil strategy for 2030. Connections are expected to be made with the EU proposal for a nature restoration law, which includes binding targets, and environmental reporting, and the new approach for a sustainable blue economy in the EU20. It will support R&I activities that help maintain ecosystems in good ecological condition and a clean and healthy environment for the EU, including water, soil and air. This will contribute to the implementation of relevant policies such as health, climate adaptation and mitigation, disaster risk reduction, sustainable circular bioeconomy and blue economy. The R&I activities will also reflect the strong interconnections between, e.g. the EU biodiversity strategy for 203021 and the farm to fork strategy, as well as the pollinators initiative23.

Relation to wetlands /restoration / climate change	Activities under Cluster 6 will support the new innovation agenda for Europe and help accelerate the ecological transition required by the European Green Deal5 in order to achieve climate neutrality by 2050. This will be done by preserving Earth's natural carbon sinks and stocks in ecosystems, including soils and plants, forests, farmed lands and wetlands and the marine environment. This will substantially reduce GHGs from the forestry and agricultural sectors and transform the food system. Actions should improve the understanding of the interactions between the changing climate system, changes in biological diversity and pollutant levels, including climate-driven ecosystem changes that are affecting natural emissions, such as wetlands (CH_4), wildfires (CO_2, black carbon), pollutant deposition or transfer and bioaccumulation in marine systems. Specific attention will be given to paludiculture, complementing the activities of Cluster 5 in the 2021/2022 work programme. R&I activities will help increase soil organic carbon, protect carbon-rich soils (e.g. grasslands and peatlands), restore peatlands and wetlands, and improve advisory services for land managers. HORIZON-CL6-2023-BIODIV-01-3: Interdisciplinary assessment of changes affecting terrestrial and freshwater ecosystems, building on observation programmes HORIZON-CL6-2023-BIODIV-01-4: Nature protection: Better methods and knowledge to improve the conservation status of EU-protected species and habitats HORIZON-CL6-2024-BIODIV-02-1-two-stage: Demonstrating Nature-based Solutions for the sustainable management of water resources in a changing climate, with special attention to reducing the impacts of extreme droughts HORIZON-CL6-2024-CLIMATE-01-2: Socio-economic, climate and environmental aspects of paludiculture
Eligible for funding	Public and private organisations. Lead partner must be a scientific institution.
Co-Financing	For scientific institutions 100 %. For NGOs 90 % on average
Deadline	20 of September 2023

6. Conclusions and recommendations

Low-water management is becoming more important in regard of prolonged dry periods in the future. Additionally, temperatures in urban areas could rise much more than the global average. Already now, with sinking groundwater levels, there are indications of conflicts between drinking water production and nature conservation.

New, future-oriented solutions must be found to better deal with the climate factors of heavy rainfall, flooding, drought and heat, as well as for the changes in society, the environment and the economy. Rainwater must be managed in a way that it is more in line with the natural water balance. Urban waters should be re-naturalized and developed into „blue-green axes" of ecological connectivity, since the shading and evaporation of vegetation measurably and perceptibly reduce ambient temperatures. Vegetation that uses primarily rainwater, but also groundwater or treated wastewater, for its adequate irrigation has a particularly favourable effect.

This flashlight study on climate and lakes presents a number of research findings and publications without claiming to be exhaustive. Together with the practical examples and case studies listed, the flashlight study provides a basis for initial conclusions and recommendations, which are summarized below in the form of central theses for further discussion.

In addition to already recognizable changes in weather, wind, and especially temperatures, which can be partially extrapolated for the future, ecological conditions (e.g. expansion of non-native species) and additional utilization demands that are expected in the future or are already emerging are changing at the same time, such as the use of cooling water and aquaculture practices.

Overall, many lakes and wetlands are already at or beyond the limits of their hydrological and ecosystem capacity. It must be ensured that current and past successes in the management of water bodies are not undone by negative developments and new demands. Therefore, existing uses of and on lakes and wetlands as well as additional demands must be critically examined and prioritized against the background of expected climate developments. This aims to reduce the overall burden on ecosystems and safeguard the ecological balance.

Eutrophication is considered to be one of the main causes of failure to achieve the good ecological status of surface waters formulated in the Water Framework Directive. Nitrate pollution is considered to be the main factor in failure to achieve the good chemical status of groundwater. Current climate research on lakes and their catchments points to factors that will lead to additional nutrient inputs and thus to increased algal blooms in water bodies. Targets and frameworks to reduce nutrient inputs should give greater consideration to both the increased likelihood of additional inputs from the watershed, for example from heavy rain events, and other additional pressures.

In addition to the data collected by the responsible agencies at the federal and state level, other institutions, such as water suppliers or „Citizen Science" projects, have comprehensive measurement data. Partially this data has been available for many years and hence should be consulted to a much greater extent for the inventory and the derivation of necessary measures. With regard to nutrient pollution, this also applies in particular to all data collected in connection with agricultural management.

When water suppliers report the lowest groundwater levels ever measured, this can be seen as a further indication of a large-scale decline in groundwater-dependent wetlands and small water bodies as well as lake areas. The extent of this trend that has occurred to date and its overall effect on aquatic biodiversity decline does not appear to be fully understood at this time. In addition to the need for research, there are a number of approaches, such as natural water retention, which are becoming increasingly important in terms of both biodiversity conservation and climate protection. Particularly effective in terms of reducing CO_2 and methane emissions are the raising of water levels and the rewetting of peatlands, of which 98% are artificially drained. A major focus of action is on former peatlands drained for agricultural use, which, along with livestock farming, are among the hotspots of agricultural climate gas emissions. Here, it is necessary to expand the protection of peatlands for reasons of nature conservation and climate protection - and climate adaptation - and to significantly expand measures for adapted use under humid conditions (paludiculture). The supply of wet sites for conventional cultivation must end.

In their current state, many lakes are so stressed by human activities so they cannot withstand climate change unscathed. In times of warming and summer drying, they need even better protection. This means, above all, the consistent avoidance of pollutant inputs, the renaturation of the shores and an extremely restrained use of their water for irrigation and cooling.

Planned measures of further bank protection should be more strongly subject to strategic environmental assessments, taking into account the limited carrying capacity of the lakes. More extensive buffer zones and unused riparian strips should be created and natural shallow water zones should be restored more extensively. To improve funding opportunities, nationwide funding programs for the renaturation of lakes and wetlands would be a good idea.

A strategy paper originally commissioned by the Ramsar Convention on Wetlands formulated ten recommendations for scientists, practitioners, and policy makers to identify opportunities for action and perspectives, and to stimulate discussion with the goal of developing a new direction for global wetland conservation in a changing world. An important goal is to significantly reduce non-climatic stressors to ecosystems: Reducing the negative impacts caused by human activities increases the resilience of habitats and species to the impacts of climate change.

If climate change and variability are not proactively addressed, the chances of success of long-term protection and conservation plans are significantly reduced. Invasive species control measures are also essential in this regard, as changing climate conditions increase the risk of the spreading of invasive species. According to statements in the extensive scientific literature currently available, it is very likely that projected climate change will increase total phosphorus loads to lakes and, generally due to cyanobacteria, lead to a decline in the ecological condition of water bodies. Adaptation measures in northern temperate zones include consistent sustainable agriculture, improved nutrient and soil management with reduced nutrient losses to surface waters, reduced point source pollution, restoration of degraded wetlands, riparian zones, and restoration of channelized rivers. In drier southern Europe, human water use must be curtailed, especially in irrigated agriculture. The success of these measures will depend largely on involvement of local communities in the adaptation process.

The study also shows that there are many factors within each sector (scientific, public, private, civil organizations) that need to be considered when analyzing the impacts of climate change on lakes. Among these factors, it is important to keep in mind that they may interact with each other and amplify or counteract the impacts. Proposals need to emerge from these multi-stakeholder and multi-sector networks, to advance knowledge, but also to take action towards ecological balance and good status of water bodies as defined by the Water Framework Directive. The present study “Lakes and Climante Change in Europe” aims to contribute to this.

Living Lakes

European Association

Co-funded by
the European Union