BIOMONDO Pilot 2

Impact of changes in water temperature and heat waves on freshwater fish diversity

Introduction

Lake surface water temperatures have been rising rapidly globally (on average 0.34° C per decade between 1984 and 2009) (O'Reilly et al., 2015). Additionally, lake heat waves intensity and duration are expected to increase with future climate change, exacerbating the effects of long-term warming (Woolway et al., 2021). Lake ecosystems are vulnerable to these temperature changes: directly by pushing to or exceeding species and ecosystems limits of resilience, and indirectly through for example decreasing amount of oxygen in the water, altering stratification or algae blooms altering oxygen availability. Accurate data on surface water temperature (SWT) is therefore crucial for estimating impacts on biodiversity. EO data can complement or replace (incomplete, point based) in-situ SWT, or give more (spatially/temporally) detailed estimates compared to modelling products. Ideally, these data would have a daily temporal resolution in order to capture heat waves. Data covering a large temporal range would allow studying changes over longer periods of time (years/decades). If the spatial resolution is higher than the lake of interest, spatial differences can also be captured in the analysis. This would also allow avoiding the influence of mixed pixels, which includes land surface temperature.

The objective of this BIOMONDO pilot is to explore the possibilities of using a combination of EO data on SWT and thermal tolerance of freshwater fish species to quantify the impacts of increases in temperature and heat waves on freshwater fish diversity.

This objective contributes to the science question "How will the diversity of life and ecosystem services in freshwater systems change with increasing climate change?". To achieve this, we first build and evaluate a predictive model of freshwater fish species' physiological tolerance to maximum water temperature, as an extension of the existing GLOBIO-Aquatic model (Janse et al., 2015; Barbarossa et al., 2020). We'll then apply this model to assess the impact of increases in water temperature and heat waves on freshwater fish diversity at several pilot sites using EO data on water temperature.

To model freshwater fish species' physiological tolerance to maximum water temperature, we will retrieve species-specific data on heat tolerance (critical thermal maximum) from existing databases (Comte and Olden, 2017; GlobTherm by Bennett et al., 2018; Leiva et al., 2019) and a systematic literature review. Next, we establish a phylogenetic regression model that estimates the heat tolerance (critical thermal maximum) of a given species as a function of the species' morphological and ecological properties, their phylogeny and their ability to acclimate to heat. We will test the predictive ability of the models based on (block) cross-validation to evaluate how it performs for species that were not included in the model training.

We will use the resulting species-level model to assess the impact of changes in water temperature and heat waves by evaluating the potential exceedance of thermal limits for the freshwater fish species occurring in a selection of pilot sites. This requires a list of species occurring at each site, and a daily timeseries of SWT, preferably covering multiple years/decades, and with an as high as possible spatial resolution. If data availability allows, model estimates can be compared with reported heat-induced fish kills. Pilot sites were selected based on the availability of data (SWT, fish species, validation data) needed for the impact assessment (see below). The chosen pilot sites are Lake Balaton (Hungary), Lake Geneva (Switzerland), Lake Mälaren (Sweden) and Lake Victoria (Tanzania, Uganda and Kenya), as well as Lake Marken/IJsselmeer (NL) in parallel with the eutrophication pilot (7.1.1).

Obtaining remotely sensed SWT with a high resolution (both spatial and temporal) is challenging. Various satellite systems (e.g. Landsat series, Sentinel-3, MODIS, AVHRR) carry sensors that can record thermal radiation. To be able to retrieve the SWT, the emissivity of water (~0.991, Wang et al. 2015) and the atmosphere as well as other atmospheric influences (absorption, scattering, transmission) must be corrected. In the case of freshwater systems, it should be noted that the derived thermal radiation temperature corresponds to the so-called skin temperature, i.e. it originates from an approximately 500 µm thin area located at the interface between water and air (Pareeth et al. 2017). Stratification and wind on the water surface result in a skin temperature that is cooler than the in-situ measured kinetic bulk temperature. Nevertheless, various studies show that both temperatures are strongly correlated (R^2 often > 0.9), i.e. for Landsat (Simon et al. 2014).

The coarse spatial resolution of most thermal sensors (> 1 km for Sentinel-3, MODIS, AVHRR etc.) is a challenge for the analysis of many freshwater systems. Only larger freshwater bodies (>100 km^2) can be captured with this coarse resolution. For smaller freshwater systems, Landsat sensors that have a higher spatial resolution but lower temporal resolution, must therefore be used. This raises the question of whether large-scale and small-scale sensors can be combined in time series. Such combinations could also reduce limitations with frequent cloud coverage.

Several SWT products are available from existing services, i.e. Copernicus Land service or the ESA Climate Change Initiative, covering the coarse spatial resolution (1 km) and the time period from 1995 to today. With these products, it is necessary to evaluate whether their spatial resolution is sufficient for biodiversity studies. To achieve the highest possible temporal resolution and to be able to go back as far as possible into the archives, these services are built on the combination of different thermal sensors. For higher spatial resolution sensors, the Landsat Collection 2, Temperature Product, is available (~100 m) and covers the period from 1984 to today. Nevertheless, the temporal resolution with an 8-day revisit time is rather low and potential cloud coverage is further reducing the availability of usable products.

For BIOMONDO we are aiming to combine multiple available EO-based SWT products to retrieve the highest spatial and temporal resolution possible. We will then compare the result with air temperature data (ERA5 reanalysis) as well as modelled water temperature data to check whether the spatial and temporal resolution of the SWT product is sufficient to pick up heatwaves. Modelled water temperature data with a global extent are available from the the DynWat model (Wanders et al., 2019) or Delft3D (for the Markermeer). If the resolution of the combined EO-based SWT product falls short, we may combine it either with modelled water temperature or with air temperature data. Due to high correlations of SWT to the air temperature, the high temporal resolution of the ERA5 data combined with the EO SWT data contribute valuable information for biodiversity monitoring and assessment. The novel product could be validated with in-situ surface water temperature data if available.

Pilot sites

Pilot sites for this pilot were selected based on the availability of data (SWT, fish species, validation data) needed for the impact assessment. After an assessment of data availability using search engines and our network of international collaborators, 5 pilot sites were chosen:

- Lake Balaton (Hungary)
- Lake Geneva (Switzerland/France)
- Lake Mälaren (Sweden)
- Lake Marken (The Netherlands) and
- Lake Victoria (Tanzania, Uganda and Kenya).

Table 1 shows the data availability at those sites. For all sites EO SWT data from CCI Lakes and CGLOPS are available (temporal range >10 years). Below a description of each pilot site can be found.

Table 1 Data availability in considered pilot sites. Per lake availability of in-situ data (yellow columns) and information regarding EO data (green columns).

Freshwater system	Availability of in-situ data for the suggested Freshwater System							Regarding EO data for the suggested Freshwater System	
Lake	List of fish species	Fish kills (by temperature increase)	Fish occurrence data	Description fish occurrence data	In-situ temperature data	Description in-situ temperature data (temporal/ spatial scale)	Contacts	Characteristics of the system	Potential cloud coverage
Balaton	Yes	Unknown	Yes	Surveys, representative data for 2005, 2010, 2014 and 2018.	Yes	Daily from 1975 to 2012. Between 2003 and 2021 at 5 points, with a monthly (October-May) or biweekly (June-September) frequency.	Balaton Limnological Research Institute (István Czeglédi)	Elongated, no islands, suitable for RS	Low
Geneva	Yes	Unknown	Yes	Complete survey 2012, + previous info	Yes	Real-time from April 2020 (LéXPLORE), CIPEL monthly data at two stations from 1953.	EPFL (Sébastien Lavanchy) UNIGE (Bas Ibelings) EAWAG (Ole Seehausen) CIPEL	Elongated/round, no islands, suitable for RS	Medium
Mälaren	Yes	Yes	Yes	4 stations sampled in 2016 and 2019	Yes	33 stations sampled TBD-TBD times (appr. monthly) respectively during 2016-2020.	Swedish Inst. of freshwater research and his (Alfred Sandströms)	Elongated, many islands, suitable for RS	Medium/ high
Marken	Yes	No	Yes	Per year per species using different "catching methods" (Wageningen University & Research)	Yes	In situ data measured by Rijkswaterstaat (several locations in the lake)	Deltares and Rijkswaterstaat	Round, few island, suitable for RS	Medium

Freshwater system	Availability of in-situ data for the suggested Freshwater System							Regarding EO data for the suggested Freshwater System	
Lake	List of fish species	Fish kills (by temperature increase)	Fish occurrence data	Description fish occurrence data	In-situ temperature data	Description in-situ temperature data (temporal/ spatial scale)	Contacts	Characteristics of the system	Potential cloud coverage
Victoria	Yes	No	Yes	Data in several sites, sampled in 2017 by Ole Seehausen's team is currently being processed	Yes	In situ CTD measurements taken in 2000–2001 and in 2008 (Pilla et al., 2021).	EAWAG (Ole Seehausen)	Round, some islands, suitable for RS	Medium/ high

Lake Balaton (Hungary)

With its surface area of 596 km^2, an average depth of 3.2 m, and a maximum depth of 11 m, Lake Balaton is the largest shallow lake in Central Europe. It is located in western Hungary, within the Carpatian Basin. The area of Lake Balaton is part of the Balaton-felvidéki National Park, it is a Ramsar site and it is included in the Natura 2000 network. This is favorable, as Lake Balaton represents nearly half of the natural aquatic surface area in the Pannonian Ecoregion, supporting large populations of plant and animal species. Its ecological status may therefore affect biodiversity region wide. It is furthermore an important site for European wintering bird populations and provides spawning and nursery grounds for fish (Ramsar, 2017). Among its inhabitants are significant populations of Habitat Directive fish species (EC, 1992), e.g., the asp, the razor fish, the white-finned gudgeon and the bitterling. Multiple anthropogenic pressures such as alien species, eutrophication, fishing and degradation of waterside habitats affect the biodiversity of Lake Balaton (Bíró, 1997; Istvánovics et al., 2007; Specziár, 2010). Main activities at the site are tourism and related business, fishing and reed harvesting (Ramsar, 2017).

The water temperature in Lake Balaton ranges from 0 to 29°C, with an annual average of 15°C. In the winter, the lake is often covered by ice (Somogyi et al., 2020). The water is rich in calcium-magnesium hydrocarbonate and oxygen, and gains the temperature of the air quickly due to its shallow depth (Ramsar, 2017). Water temperatures have significantly increased during the past decades. Liebherr and Wunderle (2018) studied AVHRR LSWT data from 1981 to 2016 and found significant increases in annual, spring and summer temperatures, of 0.34, 0.54 and 0.53° C/decade respectively. The lake underwent a strong eutrophication during the 1970s–1990s due to the use of fertilizers, leading to an increase in cyanobacteria (Vörös and Nagy Göde, 1993). During the last 20 years the water quality has improved as the rate of eutrophication has significantly declined.

Lake Geneva (Switzerland/France)

Lake Geneva, also known as Lac Léman, is situated between the Alps to the south and the Jura mountains to the north, and on the French/Swiss border. It is an elongated lake with a max length of 73 km, a maximum width of 14 km and a surface area of 580 km^2. As is visible in Figure 1 the western part of the lake is a small and narrow section ("Petit Lac", max. depth 76m, 4% of the water volume), while the lake is wider in the east ("Grand Lac", max. depth 310m). The lake remains stratified most of the year and the surface waters do not freeze in the main body. Mixing occurs every winter in the Petit Lac, while mixing rarely occurs in the Grand Lac (Perroud et al., 2009). Lake Geneva provides about one million inhabitants in the surrounding area with various services, including drinking water supply, recreation, or fisheries (CIPEL, 2014). The eastern part of the lake (Les Grangettes) is a Ramsar Site.

Lake Geneva is threatened by anthropogenic pressures and issues associated with human induced global environmental change, such as pollution, invasive species and climate change (Perroud and Goyette, 2010; Lane et al., 2019, CIPEL, 2019). From 1970 to 2010, a general warming trend was observed in and around Lake Geneva. Annual surface water temperature increased by 1.5°C during this period. Since 2012, the temperature of the lake bottom has increased by an average of 0.11° C/year. The warming in the lake can be related to the warming in the atmospheric boundary layer (Lemmin and Amouroux, 2013; CIPEL, 2021). This increase can continue, as the most significant features of climate change in the European mid-latitude region are a warming trend of the atmosphere and an increase in extreme weather events. The former may increase lake water temperature and the latter may cause strong fluctuations in lake water temperature (Lemmin and Amouroux, 2013).

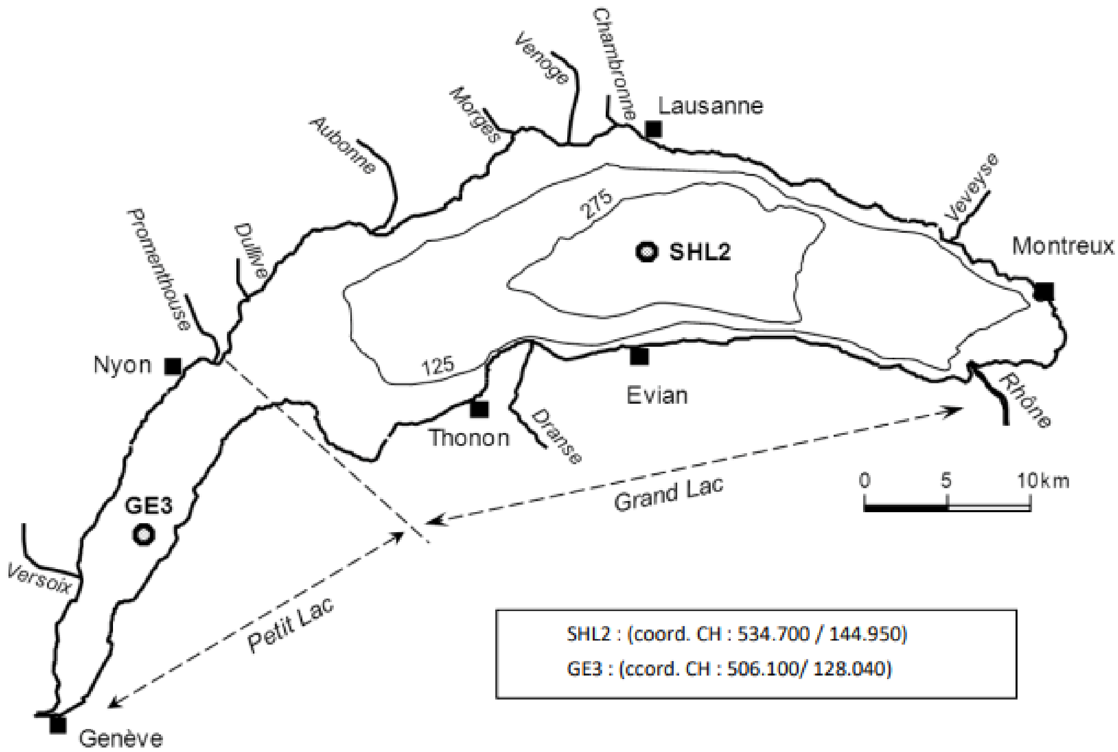

Figure 1 Lake Geneva and the location of two measuring stations (measurements include temperature) Source: CIPEL (2021).

Lake Mälaren (Sweden)

Lake Mälaren is Sweden's third largest lake (1122 km^2). It has an average depth of 12.8 meters and a maximum depth of 66 meters. Several larger rivers flow into Lake Mälaren and its catchment area also includes Lake Hjälmaren, which is Sweden's fourth largest lake, as well as a number of smaller lakes. Lake Mälaren is regulated and its main outlet, which has an average water flow of just over 160 m^3/s, is through Stockholm and into the Baltic Sea. Lake Mälaren is a typical plains lake with over 8,000 islands, islets and skerries. Its catchment area is 22,650 km^2, which corresponds to about 5% of Sweden's area.

There are about eighty nature reserves around Lake Mälaren and over forty Natura 2000 areas. In addition to these, there are also areas that have been pointed out as national interests by the Swedish regional County Administrative Boards. The area is diverse with agricultural landscapes, forested mountain areas and the archipelago. The water in Lake Mälaren is naturally nutrient-rich, which makes it sensitive to eutrophication. High levels of phytoplankton biomass have been measured, and cyanobacteria are common. During the 1960s, Lake Mälaren was heavily eutrophicated, but thanks to improved treatment plants and agricultural measures, the situation has improved. Lake Mälaren's water is very heterogeneous and the lake is divided into several administrative basins, as the conditions vary from one part to another. The lake is used for a large number of different activities, such as shipping, commercial fishing, agriculture, drinking water production and tourism. Mälaren has 34 naturally occurring fish species. The most common species are smelt, perch, roach, birch, bream and pikeperch. Smelt, which dominates the pelagic waters, plays an important role in the ecosystem as prey fish. It is anticipated that climate change will change the water level and water flows in Lake Mälaren. Climate change will also mean increasing water temperature, reduced ice cover and sea level rise which has consequences for different interests around the lakes (Eklund et. al, 2018).

Lake Marken (Netherlands)

See Pilot 1 for a description of this pilot site.

Lake Victoria (Tanzania/Uganda/Kenya)

Lake Victoria is at 1135 m a.s.l. and by area the second largest fresh water lake in the world. Its shoreline is shared by Kenya (6 %), Uganda (45 %) and Tanzania (49 %). It lies in a shallow depression between the Great Rift Valley and the western Albertine Rift and has an average and maximum depth of 132 m and 265 m, respectively. The lake receives 85% of all water input from precipitation, and only 15% from several small tributaries. Similarly, evaporation accounts for 85% of all water loss, and only a minor output is through its only outlet, the Victoria Nile in the north. The lake's surface level varies by up to 3 m, mostly in response to rainfall and only to a smaller extent to managed outflows (Awange and Ong'ang'a, 2006). Pelagic waters in Lake Victoria are stratified, seasonally variable and receive nutrients mainly through diffuse atmospheric deposition (Njiru et al., 2012). A comprehensive report on the freshwater biodiversity in Lake Victoria listed 651 species, whereof 204 are endemic to the lake, whereof again 76% are considered to be threatened with extinction (Sayer et al., 2018). Biodiversity in the lake is known to vary spatially, for example, with increasing species richness in more transparent parts of the lake (Seehausen et al., 1997). Less is known about the impact of temporal variability and temperature.

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