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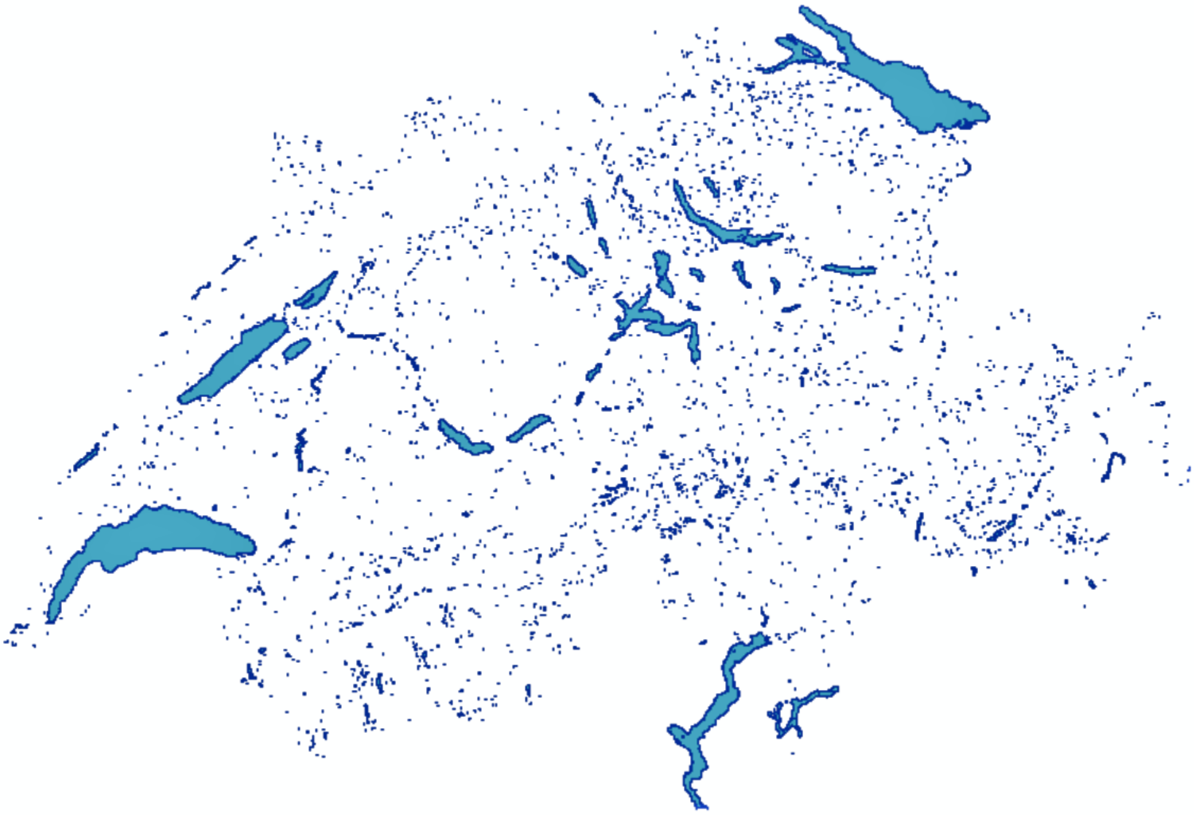
Swiss lake temperature monitoring program



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Map of all lakes of Switzerland and Liechtenstein with an area larger than 0.5 ha. Data provided by Swisstopo (2016) Vector200, Bundesamt für Landestopographie (Art.30 Geo IV): 5704 000 000, reproduced by permission of swisstopo / JA100119.

EXECUTIVE SUMMARY

Climate change and other anthropogenic factors affect lakes in many ways that can lead to important effects on freshwater ecosystems. For this reason, the Swiss Federal Office for the Environment (FOEN) is currently evaluating options to add a nation-wide lake temperature monitoring program to their monitoring activities, which already includes a network of river temperature monitoring.

In this work, we discuss the benefits and limitations of temperature data obtained by a monitoring program depending on the spatial and temporal resolution of the measurements. We conclude that for accurately observing trends in the thermal structure of lakes caused by climate change, a high time resolution is required that cannot be provided by traditional temperature profiling. We therefore recommend installing moorings where temperature can be continuously monitored.

Individual lakes react differently to climate change according to internal and external parameters, such as their size, trophic state, or altitude. These different reactions should be considered when selecting lakes to be included in the monitoring network. We therefore discuss the factors that influence a lake’s reaction to climate change, and present four different scenarios for a monitoring network. The first scenario includes the modelling of lakes that are currently monitored, without adding new monitoring sites. The second scenario represents the installation of moorings in all lakes above a certain size. The third scenario is the monitoring of lakes at different altitudes. Scenario 4 is a combination of Scenario 2 and Scenario 3 with the addition of other lakes with various characteristics to broaden the perspective. The advantages and disadvantages of the four scenarios are assessed.

Finally, we discuss the opportunity of measuring other parameters (e.g., meteorological forcing, chemical parameters…) that would increase the coherence and impacts of the monitoring program. We also shortly discuss options for data management and data quality control.

TABLE OF CONTENTS

1 INTRODUCTION

The Swiss Federal Office for the Environment (FOEN) is currently evaluating options to add a nation-wide lake temperature monitoring program to their monitoring activities, which already includes a network of river temperature monitoring. The objective of this report is to provide an assessment about the following questions from the perspective of a research institute:

- Why do we need a lake temperature monitoring?
- What are the characteristics that a monitoring system should take into consideration?
- What should be considered in selecting monitoring locations?
- What should be considered in designing a monitoring system?

In this work, we first focus on the reason and the objectives of the monitoring program (Section 2). We then present different existing monitoring systems in Switzerland and in other countries (Section 3). Afterwards, we discuss the benefits and limitations of temperature data obtained by a monitoring program depending on the spatial and temporal resolution of the measurements (Section 4) and on properties of the lakes included in the monitoring network (Section 5). Finally, different scenarios for a monitoring network are presented (Section 6), and optional complimentary measurements and data management are discussed in Sections 7 and 8.

2 MOTIVATIONS AND GOALS FOR A LAKE MONITORING PROGRAM

2.1 MOTIVATIONS FOR A LAKE TEMPERATURE MONITORING PROGRAM IN SWITZERLAND

Switzerland is often considered as the “water tower” of Europe and feeds the largest European rivers with water. Despite the limited surface, the water cycle over Switzerland is very complex and requires an integrated monitoring of all constituents including the cryosphere, rivers and lakes. With an altitudinal distribution ranging from high altitude newly formed small proglacial lakes to peri-alpine large lakes, lakes are a fundamental part of the Swiss territory. Lakes have been recently recognized as sentinel of climate change (Adrian et al. 2009), yet this role can only be achieved with proper monitoring of the change of lake temperature or more importantly of the change of the lake thermal structure.

Building up a national temperature monitoring network for lakes is a paradigm shift compared to the present situation where lake monitoring is performed by the cantonal agencies. This shift can be justified by the fact that climate change is currently superseding eutrophication as the major threat to lakes in Switzerland. Eutrophication was caused to a large extent by the load of nutrients from the catchment of a lake and required individual solutions and adapted monitoring for each lake and catchment. Conversely, even though the impacts of climate change on a specific lake are modulated by the lake’s characteristics, they are expected to be qualitatively similar for similar lakes all over Switzerland as well as in Central Europe. A national lake temperature monitoring network will thus yield valuable information for the nationwide management of lakes and will also contribute to international efforts to adapt to climatically induced changes in aquatic ecosystems.

2.2 AIMS OF THE MONITORING PROGRAM

The aims of the lake monitoring program as defined by FOEN, can be summarized as follows:

1) Recording of the current temperature as a base to assess the current state of lakes in Switzerland and the interactions between lake temperatures, physical mixing processes and subsequent potential effects on ecology and biodiversity.
2) Observation of changes in lake temperature and stratification due to climate change and other anthropogenic or natural developments.
3) Provide data that can be used to develop future scenarios for the impacts on lakes and downstream rivers due to climate change or anthropogenic activities, such as thermal use of water or alterations in hydropower production.

2.3 OBSERVED IMPACTS OF CLIMATE CHANGE

According to the National Center for Climate Services (NCCS) and their last report about climate change (NCCS 2018), Switzerland will not only face a long-term increasing trend in air temperature but also a modification of the frequency distribution of extreme events. The **surface air temperature** has already **increased** in all regions of Switzerland since the start of the instrument record of the NCCS in 1864. This warming will continue and may eventually reach an increase up to 6.9 °C (scenario RCP8.5) at the end of the century in the annual mean compared to the pre-industrial era (1864 - 1900), for a scenario that will not limit global warming to 2 °C (NCCS 2018).

The **frequency, character and intensity of extreme events will** also **change**. There will be more frequent, more intense, and longer-lasting heatwaves and extremely hot days. The hottest summer days are projected to warm by 3.9 - 9.4 °C, and very hot days that on average occur on about one day per summer today are projected to occur during 2 to 5 weeks per summer by the end of the 21st century, depending on the model and region (NCCS 2018). Heavy rain is also projected to intensify, with day-long heavy precipitation events (100-year return levels) that are projected to increase by 10 - 25 %, depending on the season and region (multi-model medians). In summer, a reduction in wet days and a tendency toward longer dry spells (meteorological droughts, i.e., periods with no rain) is expected in response to strong warming (RCP8.5 at the end of the 21st century, low to medium confidence).

In the context of this anthropogenic climate change, the thermal properties of Swiss lakes are expected to change as well. **At a global scale, the average increase in lake surface temperature measured over the last decades was about 0.3 °C/decade** (O'Reilly et al. 2015). The average warming of Central European lakes in the last three decades was similar, and showed significant seasonal variation with stronger warming in spring and summer (Woolway et al. 2017). Switzerland experienced increasing lake temperature as well (Fink et al. 2014) with, for instance, the mean temperature of Lake Constance increasing by 0.17 °C/decade from 1962 to 1998 (Straile et al. 2003). In the deep water, consistent warming rates of 0.1 to 0.2 °C/decade were observed in Europe (Dokulil et al. 2006). **Yet, these observed warming trends are subject to a strong variability depending on the lake characteristics, its catchment and its location.**

While the worldwide changes in lake surface temperature are well documented, the assessment of **changes in the thermal structure of lakes** associated to climate change is more complex. We refer to the thermal structure as the vertical distribution of the temperature. An important parameter is the strength, vertical location and duration of the thermal gradient separating the surface from the deep water in a thermally stratified lake (see also section 2.4.3).

The changes in temperature and stratification will have **strong impacts on lake water quality and ecology**. An extended duration of the stratified period will prolong the time available to consume oxygen in the hypolimnion and increase the duration and the volume affected by anoxic conditions (Schwefel et al. 2016). **Hypoxic conditions are thus expected to become much more common in the future** (Figure 1).

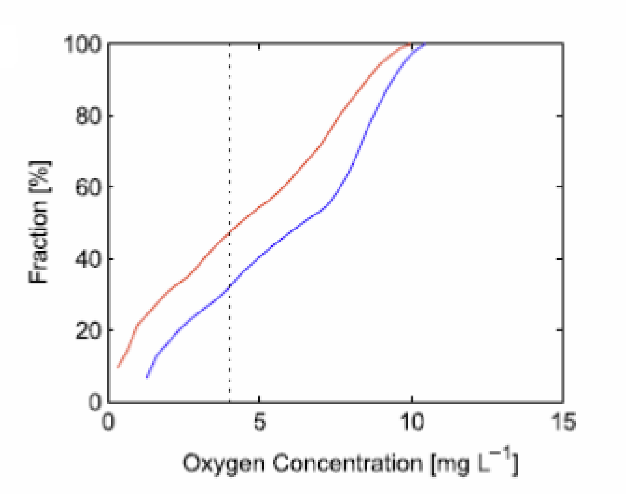


Figure 1: Cumulative sum of the oxygen concentration in the deep layer (lowest 50 m) of Lake Geneva for the period 1981-2012 (blue) and forecasts for 2070-2101 (red) (Schwefel et al. 2016). Values left of the dotted line (4 mg L^{-1}) show hypoxic conditions. This study suggests an increase by 25 % of days with oxygen concentrations below 4 mg L^{-1} in the deep layer of Lake Geneva. Figure from Schwefel et al. (2016).

This may be further exacerbated by a **reduction of the penetrating depth of winter deep mixing**, which also **reduces the recycling of nutrients from the deep to the surface waters** (Salmaso et al. 2018). For the example of Lake Zurich, this has been shown to have **severely affected the phytoplankton composition**, where the spring blooms by centric diatoms and cryptophytes have been strongly reduced, whereas the cyanobacterium *Planktothrix rubescens* was favoured by the incomplete mixing (Yankova et al. 2017). The current state of Lake Zurich is a transitional state, and it remains to be seen how it will react in the future under a mixing regime where complete mixing and corresponding nutrient supply will likely occur only every few years. Another example of the importance of lake temperatures and stratification on a shallow eutrophic lake in the Netherlands was discussed by Joehnk et al. (2008). They quantified how **heat waves can promote blooms of *Microcystis aeruginosa*, a harmful cyanobacteria**. Harmful cyanobacteria blooms are generally expected to occur more frequently in a warming climate (Huisman et al. 2018). Furthermore, the **warming is a threat for cold-water fish**, whose habitat may shrink both from above, where temperatures exceed their tolerance, and from below, where oxygen concentrations may become too low (Jiang and Fang 2016). In general, increasing temperatures are expected to be a threat to the survival of several fish species and for their reproduction. Indeed, **temperature changes affect fish in many ways**, such as the growth and general condition, behaviour, reproduction, migration and health (Burkhardt-Holm et al. 2002).

From a greenhouse gas perspective, the fundamental role of lakes as regulators of carbon cycling and climate has only recently been recognised (Tranvik et al. 2009). The burial of organic carbon in the sediments of lakes and oceans has been estimated to be similar to that in the oceans (Mendonça et al. 2017). Yet**, the temperature increase may disturb the traditional function of lakes acting as sink of organic matter** by increasing the reaction rate of organic carbon mineralisation. In lakes, organic matter is either mineralized in the water column or the surface sediments, or buried into the deep sediment. The organic carbon mineralization being partly temperature controlled (Gudasz et al. 2010), an increase in lake temperature will lead to a smaller fraction of organic matter burial (Figure 2) and increase the greenhouse gas evasion. Furthermore, an increased duration and extent of anoxic conditions in the deep water of lakes will likely increase the fraction of mineralized carbon that is emitted from lakes as methane rather than carbon dioxide to the atmosphere.

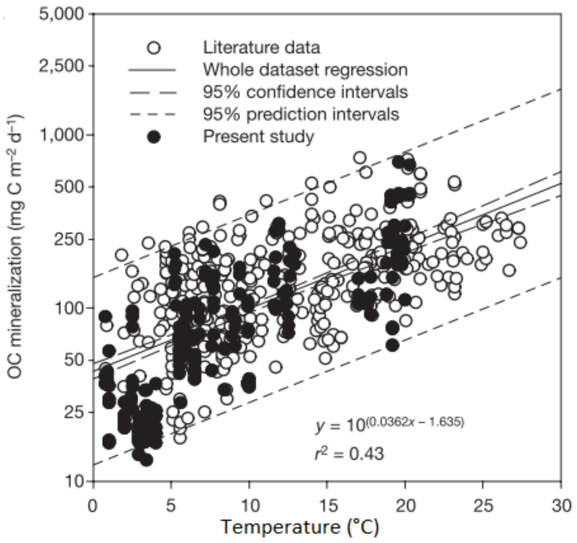


Figure 2: Temperature dependent organic carbon mineralization in lake sediments (Gudasz et al. 2010).

Climate change is expected to affect ecosystems also due to the **temperature-dependence of metabolism**. Figure 3 shows the temperature dependence of 64 metabolic processes including, e.g., growth, feeding, respiration, and movement of a broad range of aquatic organisms (Kraemer et al. 2017). Within certain limits, the corresponding process will respond exponentially to increasing temperatures, and the temperature-dependence is stronger if a process has a high activation energy. Due to the exponential relationship, changes in metabolic rates are expected to be larger at high temperatures, i.e., in lakes at low latitudes and altitudes.

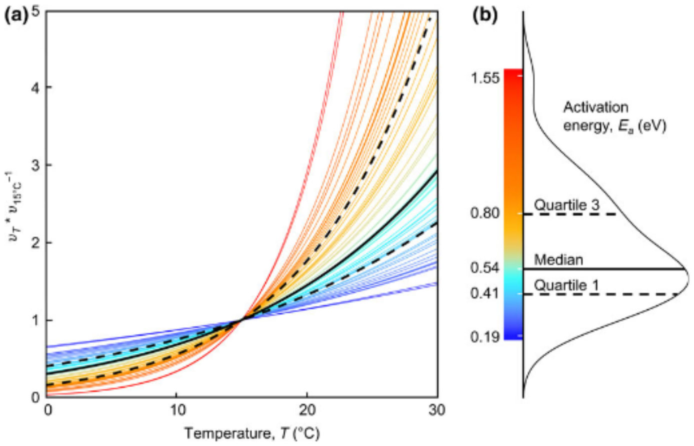


Figure 3: a) Exponential temperature dependence curves for 64 metabolism-linked variables. Metabolism-linked variables are expressed as υ_T (value of each metabolism-linked variable, υ, estimated at temperature, T) divided by $\upsilon_{15°C}$ (the value of υ estimated at T=15°C). The line colours indicate the activation energy of the individual processes. The full density distribution of activation energies represented in this study is presented in b). The solid, black, horizontal line represents the median activation energy (0.54 eV) and the dashed lines represent the first and third quantiles (0.41 and 0.80 eV, respectively). The activation energy represent the energy which must be provided to a system to start the process. Figure adapted from Kraemer et al. (2017).

Climate change also **affects the duration and extent of ice cover** on Swiss lakes. For lakes that freeze over every year, ice cover duration has significantly decreased (e.g., Lake St. Moritz; Livingstone, 1997), while freezing became rarer on lakes where this occurs only in cold winter (Franssen and Scherrer 2008). Climate change is also responsible for the **glacier retreat often followed by the development of proglacial lakes** (Carrivick and Tweed 2013). Those new lakes are **changing the initial temperature and particle concentrations** of the downstream rivers. The suspended solids concentration downstream of the proglacial lakes will significantly decrease by up to 95 % compared to the situation without a lake (Geilhausen et al. 2013), which will have strong impacts on hydrology, river ecology and reservoir management. Moreover, proglacial lakes influence the glacier melting, and affect the local and regional weather by albedo and thermal heat capacity controls (Carrivick and Tweed 2013). The future evolution and the ability to correctly model downstream water quality depends on the dynamics of proglacial lakes. Such systems have deserved little attention in the past and should be monitored, especially given the topography of Switzerland and given the fact that they are expected to increase in number and size (Carrivick and Tweed 2013).

A final example of the impacts of climate change are the potential effects on drinking water supply. Climate change, especially because of temperature increase and heavy rainfalls, will probably lead to a **rise of dissolved organic matter, micropollutants and pathogens** in surface water, which will lead to a **degradation of drinking water quality** with potential impacts on health (Delpla et al. 2009).

All the environmental changes presented above have in common to largely depend on the change in lake **thermal structure** (change in **absolute temperature and stratification**). Water temperature impacts on a variety of other parameters and makes it a subtle, but vital, factor in determining water quality.

2.4 PARAMETERS CHARACTERIZING THE THERMAL STRUCTURE

We showed above that ecological responses of lakes depend more or less directly on their **thermal structure**. However, the thermal structure varies in time and depth as exemplified for Lake Zurich in Figure 4. The thermal structure varies seasonally, with a stratification period in summer and mixing events in winter.

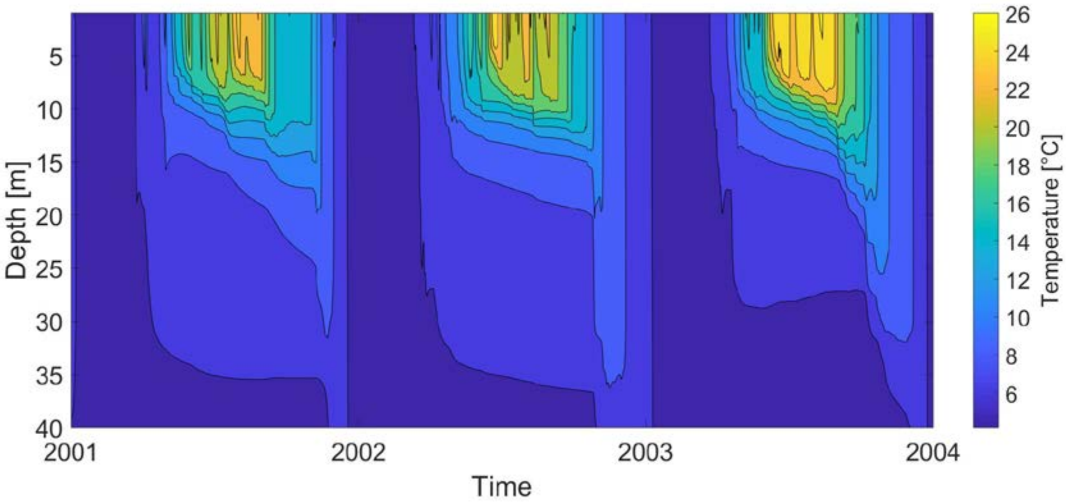


Figure 4: Contour plot of temperature [°C] from 01.01.2001 to 01.01.2004 in the top 40 meters of Lake Zurich. 4, 6, 8, 10, 12, 14, 16, 18, 20, 22 and 24 °C isotherms are shown. Data modelled and validated, are obtained from Schmid and Köster (2016). See section 4.1 for more details regarding the data.

It is thereby crucial to **correctly monitor the temporal and spatial evolution of the thermal structure** of the lakes. The parameters listed below can be used for this purpose.

2.4.1 Surface temperature

The dynamics of lake surface temperature are closely related to air temperature (Livingstone and Lotter 1998; Piccolroaz et al. 2013) (Figure 5a). However, due to the thermal inertia of the water, the maxima and minima of surface water temperature are delayed compared to those of air temperature. The inertia, und thus the delay, will be larger in lakes with a deep surface mixed layer, i.e., in large, deep, and clear lakes. Lake surface temperatures are further affected by other meteorological variables (wind, solar radiation, humidity), by the transparency of the lake water, and eventually by the river inflows and outflows in lakes with short water residence times.

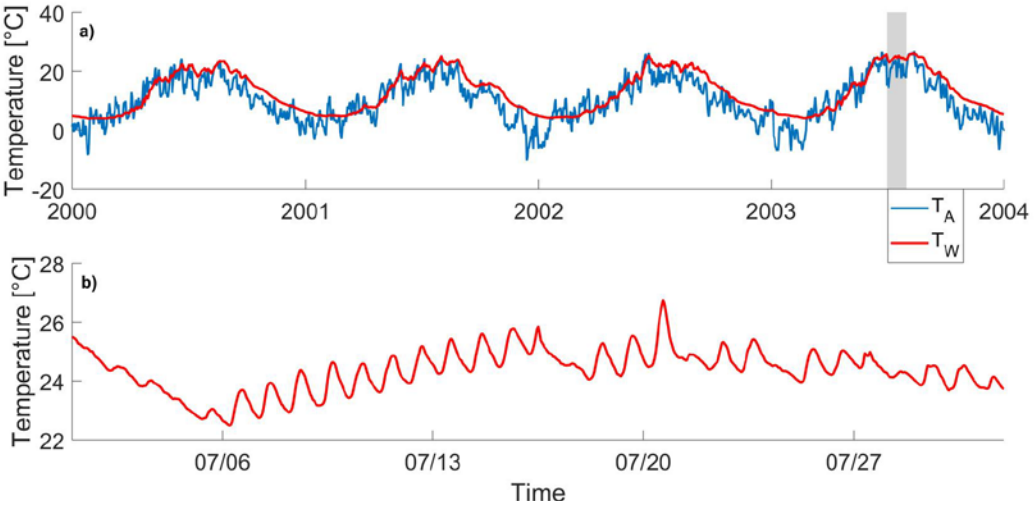


Figure 5: a) Time series of air temperature T_A (blue line) and simulated lake surface water temperature T_W (red line) for Lake Zurich between 01.01.2000 and 01.01.2004; b) simulated lake surface water temperature for July 2003, marked in grey in subplot a). Air temperatures were registered by MeteoSwiss (station Wädenswil) and the lake surface temperatures (1 m depth) were modelled from Schmid and Köster (2016).

Measuring surface temperature is possible from *in-situ* observations or remotely sensed satellite observations (Riffler et al. 2015). In small lakes, horizontal variability of temperature can be negligible, and temperature measurements directly at the river outlet can provide time series of surface temperature. In larger lakes, this is not necessarily the case. For example, a measurement campaign in May 2007 in Lake Constance showed surface temperature variations of up to 8 °C along the lake (Rinke et al. 2009). Similar results were found for Lake Geneva using remote sensing and model data (Bouffard et al. 2018). In summary, lake surface temperature data are relatively easy to obtain but have a fast, daily, temporal variability. An example of this fast temporal variability is presented in in Figure 5b. Finally, lake surface temperature doesn’t provide the information required to assess temporal changes in the thermal structure of a lake.

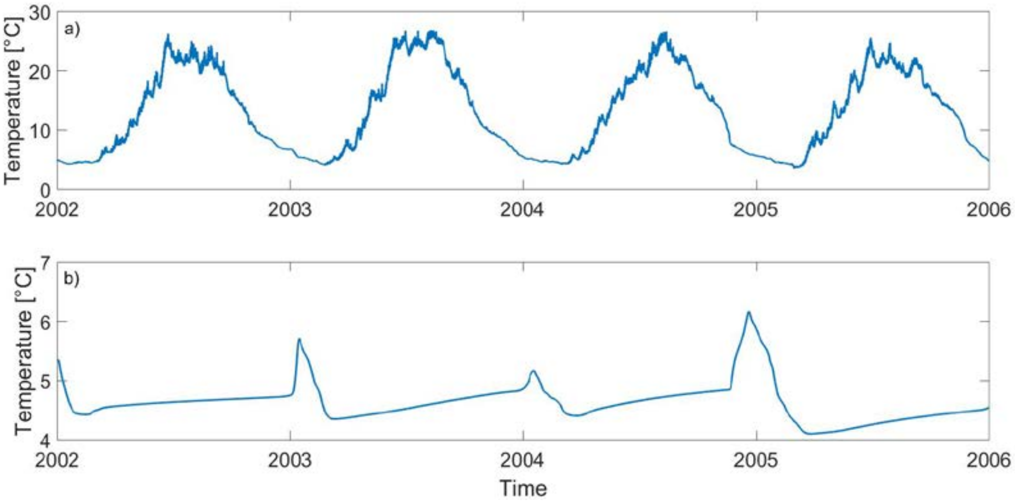


Figure 6: Simulated surface (a) and bottom (b) temperature [°C] from 01.01.2002 to 01.01.2006 in Lake Zurich. Note the two different y-axis values. Surface temperature (1 m) is highly affected by daily meteorological variability and fluctuates fast, while bottom temperature (135 m) is predominantly affected by mixing events in winter. Data were obtained from Schmid and Köster (2016). See section 4.1 for more details regarding the data.

2.4.2 Bottom temperature

In contrast to the surface temperature that can be remotely measured, the temperature in the water body, and especially the lake bottom temperature, can only be measured with *in-situ* sensors. Yet, bottom temperatures in deep lakes vary only slowly and are not affected by daily fluctuations. They are predominantly related to lake morphometry and mixing events in late winter or early spring (Hondzo and Stefan 1993). The second plot in Figure 6 represents the bottom temperature variations in Lake Zurich. Every late winter the bottom water temperature is modified by the seasonal deep mixing. Subsequently, the temperature slowly and continuously increases during the stratified period due to thermal diffusion. The seasonal variability is minor when compared to the surface temperature.

2.4.3 Mixing regime

The density of freshwater depends on its temperature. It is highest around 4 °C, and both colder and warmer water have a lower density. In lakes, the surface temperature during summer is warmer and thus less dense than the bottom water temperature. This density difference inhibits vertical exchange, e.g. of oxygen or nutrients, between the surface and the deep water. A lake is stratified, when such a density difference between the surface and the bottom waters exist. Besides the normal case of summer stratification, a lake can also be inversely stratified in winter, if the surface water is colder than 4 °C. Such inverse stratification is a precondition for freezing.

Lakes can be classified according to their mixing regime (Boehrer and Schultze 2008):

1. Meromictic lakes never (or extremely rarely) experience a complete overturn.
2. Holomictic lakes overturn at least once a year. Holomictic lakes are subdivided into classes according to the frequency and time of overturns:
    a) Oligomictic lakes experience overturn less frequently than once a year. Mixing usually occurs in winters at irregular intervals, triggered by cold winter temperatures and/or strong wind.
    b) Monomictic lakes experience overturn once a year, and are stratified the rest of the year.

c) Dimictic lakes experience overturn twice a year, between two stratification periods (usually with normal stratification in summer and inverse stratification and possibly ice-cover in winter).
d) Polymictic lakes are completely mixed several times every year. In temperate regions, this is usually the case only for very shallow lakes.

The mixing regimes of the major Swiss lakes are given in Appendix 10.1. Other regimes exist but are not described here as they are not relevant for Swiss lakes.

Mixing regimes are already changing and the transition will continue with climate change (Livingstone 2008). For instance, some monomictic lakes may shift to an oligomictic or meromictic regime. This can have important consequences, for example for oxygen supply to the deep water or primary production in the surface water of the lake. Such shifts in mixing regime can represent a significant socio-economic risk. For example, monomictic lakes currently used for drinking water supply could shift to a meromictic regime, which would threaten their drinking water supply capacity.

It is therefore crucial to monitor the mixing regime of lakes. Moreover, monitoring the mixing regime is the key to monitoring the duration of summer and winter thermal stratification.

2.4.4 Duration of stratification and mixing

The duration of the summer thermal stratification is expected to be altered by climate change (Robertson and Ragotzkie 1990) and will tend to last longer (Beutel and Horne 2018), thus having important effects on many parameters such as the dissolved oxygen concentration of the deep waters, one of the key parameters of ecosystem quality (Fenocchi et al. 2018). Similar to the duration of stratification, the duration of mixing is crucial for aquatic ecosystems as it influences the re-oxygenation of the deep-waters and the export of nutrients from the hypolimnion to the epilimnion, limiting the accumulation in the former (Yankova et al. 2017). The duration of mixing is expected to be altered by climate change, affecting deep water ecosystems (Fenocchi et al. 2018).

2.4.5 Position and strength of the thermocline

It is not only important to know whether or not a lake is stratified but it is also important to monitor the position and strength of the layer stratifying the water column. This layer is called the "metalimnion" or "thermocline" and corresponds to the layer where the density (i.e., temperature) gradient is highest, thus separating the water column into two parts. The strength of the thermocline is crucial as it determines vertical exchange (e.g., of nutrients or dissolved oxygen) while its position determines the relative thickness of the warm epilimnion and the cold hypolimnion. Temperature and dissolved oxygen are two extremely relevant parameters for fish strongly affected by the thermocline (Burkhardt-Holm et al. 2002; Zhang et al. 2015). Thus, changes of the position and strength of the thermocline can lead to important effects on fish habitats.

2.4.6 Stability

The lake stability indicates how the current state of the lake will react to destabilizing forcing (e.g., cooling and wind forcing). There are several ways of quantifying the stability, such as the Schmidt stability (Idso 1973) or the buoyancy frequency N^2. The Schmidt stability is a widely used parameter that represents the amount of work needed to transform the current density distribution into uniformity. It characterizes the strength of the stratification (Schwefel et al. 2016). The buoyancy frequency is related to the local density gradient and often used to describe the vertical distribution of the stability of stratification. As shown in Figure 7c, the peak in buoyancy frequency N^2, corresponds to the maximum of the density gradient that is the thermocline. As a first approximation, the intensity of the vertical fluxes are inversely proportional to N^2. A large N^2 (i.e. large density gradient) will cause a physical separation of the deep water from the shallow water with reduced vertical fluxes.

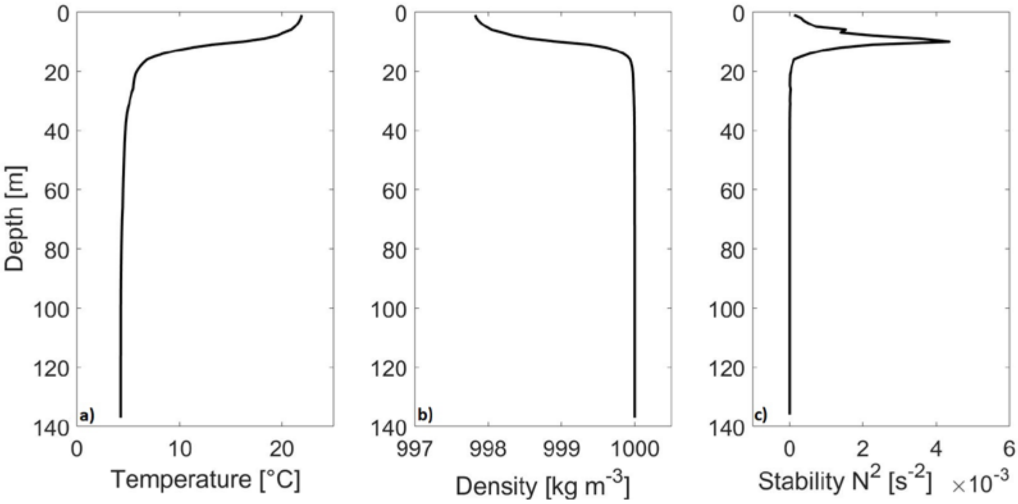


Figure 7: Profiles of temperature (a) [°C], corresponding density (b) [kg m^{-3}*] and stability (c) [s*$^{-2}$*] with depth on 29.07.1996 in Lake Zurich. Data were obtained from Schmid and Köster (2016).*

2.4.7 Heat content

The heat content is a widely used parameter that includes information on the temperature of the entire water body, not only the surface. Trends in heat content reflect the warming rates of the entire water column.

3 OVERVIEW OF EXISTING MONITORING SYSTEMS

3.1 IN SWITZERLAND

Traditionally, lake temperatures in Switzerland have been monitored by the cantonal agencies (or by international commissions in the case of transboundary lakes) by **measuring vertical temperature profiles**, usually at the deepest location of a lake. Long-term monitoring data exist for most of the larger lakes of Switzerland, for some lakes at a monthly interval, for others at intervals of 3 to 6 months. A list of the major Swiss lakes is available in Appendix 10.1 with characteristics and frequency of the current monitoring program.

In general, the main focus of the monitoring has been to observe water quality parameters such as oxygen, nutrients, chlorophyll as a proxy for productivity, and in some cases phytoplankton and zooplankton composition. **Temperatures are often recorded as a by-product**. These temperature and water quality time series are **extremely valuable to assess past changes** in the lakes, both concerning the impacts of climate change (Livingstone 2003; Schmid and Köster 2016), and the history of eutrophication and re-oligotrophication (Matzinger et al. 2010; Rhodes et al. 2017). It is **very important to continue these monitoring activities**.

However, as shown in chapter 4 below, **the temporal resolution of this profiling data is insufficient to reliably estimate trends in the thermal structure.** This is especially problematic for trends in lake surface temperatures and in the duration of thermal stratification, two of the most relevant quantities for assessing climate change impacts on lakes.

In order to obtain the perspectives regarding a lake temperature monitoring system from professionals working on lakes, a **survey** was performed. It was sent to 29 scientists and consultants working on lakes, of which 16 responded. The survey mostly represents the opinion of the scientific researchers hence is an important basis for the proposed scenarios presented in section 6. Most survey respondents use lake temperature data from currently existing monitoring programs. Yet, 68.8 % of the concerned people indicated that the available data are not sufficient for their tasks. Among others, critics highlighted the need of increasing the temporal and spatial resolution (over the water column), the need of increasing the number of studied lakes, and finally the need for a standardized lake-to-lake database. Results will be presented along the report whenever appropriate, and more information on the survey, including a link to the questionnaire and the complete results presentation, can be found in Appendix 10.4.

3.2 IN OTHER COUNTRIES

There is a worldwide trend in equipping lakes with high frequency moorings, often driven by scientific networks. The largest decentralized temperature monitoring system in the world is certainly the **Global Lake Ecological Observatory Network** (GLEON), an important international community of scientists, educators, policy makers and citizens that are invested in the future of fresh waters. The aim of this network is to “understand, predict and communicate the role and response of lakes in a changing global environment” (Hanson et al. 2016). GLEON consists of 82 studied lakes across 34 countries, with more than 500 members from around the world (Hamilton et al. 2015). Every lake included in the monitoring program is equipped with instrumented buoys, measuring several parameters at high resolution, including temperature. Data from this network are available to promote coordination between local sensor measurements and the global scale perspective, in order to advance the understanding of ecological processes in lakes (Weathers et al.

2013). Some Swiss lakes (i.e. Greifensee or Lake Geneva) were included in this network for several studies even though their monitoring is not done at a high temporal frequency (Hamilton et al. 2015). They were then considered as “Lakes without high resolution data” (GLEON). However, including several Swiss lakes into this network would be highly recommended in the future, as it would allow to interpret changes observed in Swiss lakes in a global perspective and contribute to climate change assessment and corresponding joint research on a global scale.

A second example of a large temperature monitoring effort is the **Global Lake Temperature Collaboration** (GLTC), which compiled lake surface temperature from ~100 lakes worldwide (*in-situ* data) and almost 200 other lakes with remote sensing methods. In total, this collaboration involves more than 50 scientists worldwide. The GLTC focuses mostly on surface temperature and several related scientific questions are assessed, such as global and regional patterns of lake warming over the past several decades, as well as the climatic and geographic factors controlling these patterns (Sharma et al. 2015).

In Europe, the **Water Framework Directive** (WFD), adopted in 2000 by all members of the European Union, sets the objectives and standards for water protection. In addition to lakes, the WFD aims at monitoring all European water systems from source to sea (including groundwater, rivers, estuaries, and coastal waters), with a catchment area approach. Member states are responsible for the monitoring of the waterbodies lying entirely within their territory, and shall endeavour to establish appropriate coordination in the case of transboundary waters. The main goal of this monitoring program is to assess the ecological status of each water body, and to derive strategies for improving the ecological status if necessary. It also aims at assessing the long-term changes that may result from various anthropogenic activities (Ferreira et al. 2007). The water quality assessment of lakes requires measurements of vertical profiles of different parameters, including temperature, on a monthly to quarterly basis.

In the USA, The **Great Lakes Environmental Research Laboratory** (GLERL), which is part of the National Oceanic and Atmospheric Administration (NOAA) program, currently monitors the surface and bottom temperature of the Laurentian Great Lakes. In the near future, they also aim at measuring the water temperature of the entire water column, in order to resolve the thermocline (Chu et al. 2011). The GLERL monitoring system also includes meteorological data with at least two equipped buoys per lake monitoring solar radiation, cloud cover, humidity, wind speed and many other meteorological parameters, in addition to other coastal meteorological monitoring systems. Data from the monitoring system are integrated into an operational hydrodynamic model to allow short time forecasting of the state of the lakes (Chu et al. 2011). All parameters are measured every 10 minutes, and data are available in real time. Several thousand people per day access temperature and/or wind speed data on their website during the summer months (according to a personal communication with P. Chu, responsible for the Integrated Physical & Ecological Modelling & Forecasting Branch of the GLERL, USA). While most of these visitors are working on lakes, such as fishermen, staff from transportation or rescue boats and scientific researchers, there is also a significant interest from the general public. Efficient data sharing is considered as crucial to foster exchange and collaboration between different lake users and stakeholders (Chu, personal communication).

Sentinel lakes (Lacs sentinelles) is another example of a lake monitoring network including temperature measurements. This network was developed by the regional Conservatories of natural areas (Conservatoires des espaces naturels) in France. The monitoring program resulted from a joint interest of scientists and managers to understand and warrant sustainable protected natural areas. Scientists and people responsible for the natural areas are collaborating at all stages of the monitoring program from the definition of the goals and of the monitoring program, to the field work and finally to the practical assessment of the program. The monitoring program is gradually operating a transition toward high resolution temperature mooring with pilot lakes (Bonet et al. 2017). In addition to these pilot lakes, more lakes are studied with a standard protocol, consisting of continuous surface and bottom temperature measurements and occasional water quality measurements including temperature profiles (usually two per year). All data are available upon request.

This non-exhaustive list of existing temperature monitoring systems highlights their variability around the world. Some of the systems are more focused on covering a large range of different lakes (i.e., GLEON) while others tend to focus only on lakes that share some common characteristics (i.e., Sentinel lakes focusing on high altitude lakes), and they apply different monitoring methods. Nevertheless, for the build-up of a consistent and reliable temperature monitoring system, previous experience from these existing monitoring networks should be considered.

3.3 CONCLUDING REMARKS

Lake temperature is often a by-product of water-quality driven monitoring programs. Recent new initiatives such as GLEON, GLERL or Sentinel lakes highlight **the benefits of high frequency temperature measurements** as a key parameter to efficiently assess the change in the ecosystem. Contrastingly, the small spatial and temporal resolution of some data collected for the implementation of the WFD has often been criticised (Irvine 2004), and similar criticisms have also been applied to the GLTC (Gray et al. 2018). Another keystone is **an efficient data management plan** facilitating data sharing and use by all communities (Benson et al. 2008; Weathers et al. 2013). This is an asset for GLEON and Sentinel Lakes but was identified as an issue on the WFD (Hering et al. 2010) which generates a huge amount of monitoring data. However, these **data** are not **centrally stored**, which drastically reduces their accessibility and use. Another criticism of the WFD is the **heterogeneity of original data** collected by different countries with different sampling methods (Hering et al. 2010). This highlights the importance of **applying uniform and consistent methods for globally monitoring lake temperature** to maximise efficient use of the collected dataset.

4 SPATIAL & TEMPORAL VARIABILITY – ANALYSIS, DESCRIPTION AND RESULTS

4.1 METHODOLOGY

In the previous chapters, we have documented the **need for a monitoring of the thermal structure of the lake** to understand and **foresee changes in lakes in the future**. We have also provided **a list of parameters** that can be derived from temperature monitoring and used to assess the thermal properties of a lake. In this chapter, we will now **assess the minimum spatial and temporal resolution** for this monitoring system to be effective. To do so, we evaluated the influences of different temporal and vertical measurement resolutions on the accuracy of several lake thermal properties. We **used a one dimensional hydrodynamic model** (Simstrat) previously calibrated and validated for Lake Zurich (Schmid and Köster 2016) to construct a time series of 33 years of temperature with 1 m vertical and 1 hour temporal resolution.

The results that would be obtained by monitoring a lake at **lower vertical resolutions were simulated** by sampling at specific depth intervals from the complete dataset. Higher vertical resolutions were used in the top layer (every 2, 3, 4, 5, 8 and 15 meters) where the temperature is highly fluctuating during the year, and smaller resolutions (every 5, 20, 50 and 75 meters) in the bottom layer where the temperature is more stable. The uppermost and lowermost layers (top and bottom temperature) were always included in the sampling. Three different depths were tested for separating these two layers (20, 30 and 40 meters). Figure 8 is a schematic representation of a typical summer temperature profile and the sampling depths for one specific test case.

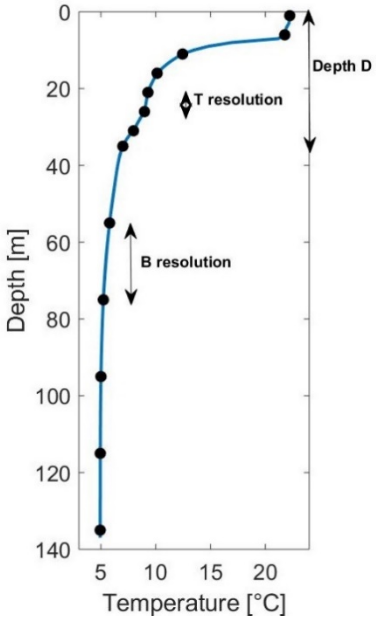


Figure 8: Typical summer vertical temperature profile (blue line), obtained from modelled data on Lake Zurich. Black dots represent the sampling depths for a 5 m resolution in the top layer T and a 20 m resolution in the bottom layer B. The two layers are separated by the depth D, here equal to 40 m.

From the sampled temperatures, the following characteristics were derived: the **position of the thermocline**, the **maximum stability** (N^2) and the **mean temperature in the epilimnion**. The importance of these parameters was discussed before in section 2.4.

Smaller **temporal resolutions** were simulated with a Monte Carlo approach. The total time series was split into weekly, bi-monthly, and monthly intervals. From each of these intervals, a measurement day was then randomly sampled. This procedure was then repeated 10'000 times, creating an ensemble of possible results from monitoring at these intervals.

We then assessed the impacts of temporal resolution on the estimated **trends of temperature** (surface and bottom), **duration of stratification** and the **duration of mixing¸** and their respective long-term **trends**, and on **heat content** (minimum, mean and maximum every year). Trends were calculated using the Theil-Sen estimator. The confidence intervals of the trends were estimated by bootstrapping.

We used Lake Zurich as an example to assess the minimum temporal and vertical resolution for a future lake monitoring. A similar analysis was done for Greifensee and showed very similar results, hence not shown here. Some differences due to the smaller depth of Greifensee were noticeable but are directly linked with the depth of both lakes. **Our results are expected to be qualitatively similar for most lakes**.

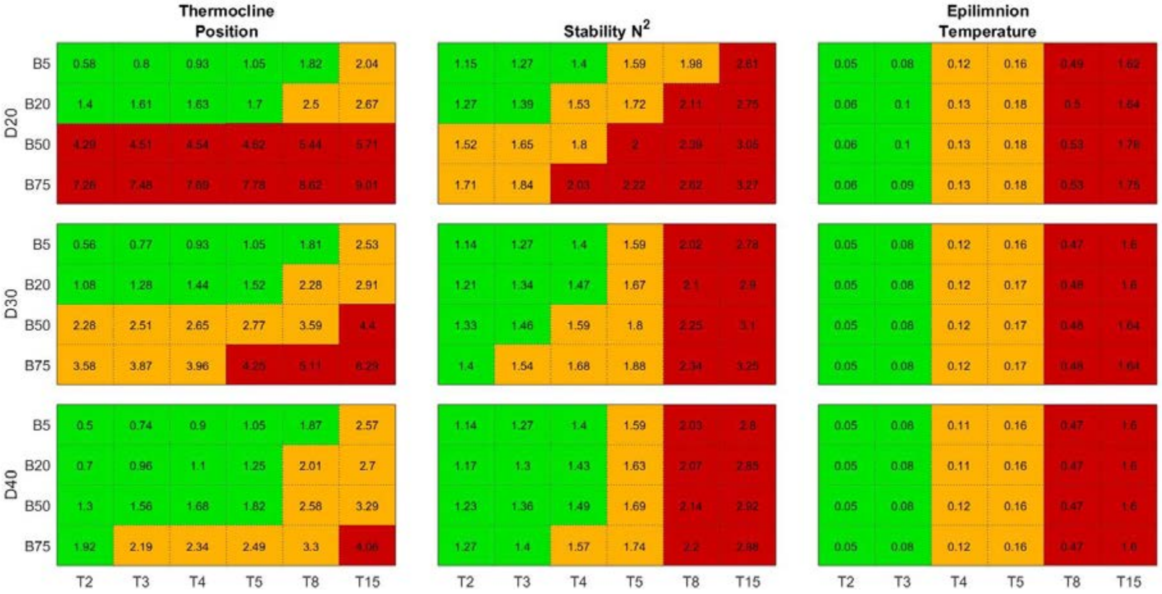
A complete description of the methodology is available in Appendix 10.2.

4.2 SPATIAL RESOLUTION

4.2.1 Results

Figure 9 shows the effects of having different vertical resolutions on three different parameters: the position of the thermocline, the maximum stability (N^2) and the mean epilimnion temperature. In order to visualize the effect of the different spatial resolutions on the accuracy of the results, a color code is applied. For each parameter, two thresholds are defined: one representing the limit between an accurate result and an acceptable result, and a second threshold representing the limit between an acceptable result and a non-acceptable result. The following thresholds were used:

- 2 meters and 4 meters for the position of the thermocline compared to the position of the thermocline obtained with a 1-m resolution. 2 m are a typical value for vertical displacements of the thermocline during a day due to internal waves in a lake. For example, a study in Lake Zurich showed vertical displacements of the thermocline and the plankton layer located therein of 1 to 2 m during calm conditions and increasing to 6 m during a storm event (Garneau et al. 2013).
- Factors of 1.5 and 2 between the stability N^2 and the stability N^2 obtained with a 1-m resolution. N^2 in the thermocline can seasonally vary by at least an order of magnitude depending on the wind intensity and distribution.
- 0.1 °C and 0.2 °C for the epilimnion mean temperature compared to the epilimnion mean temperature obtained with a 1-m resolution. These thresholds should be lower than the typical observed current trends in epilimnion temperatures of 0.3 °C per decade if such trends should be detectable within a time scale of a few decades.



Thermocline Position

		T2	T3	T4	T5	T8	T15
D20	B5	0.58	0.8	0.93	1.05	1.82	2.04
	B20	1.4	1.61	1.63	1.7	2.5	2.67
	B50	4.29	4.51	4.54	4.82	5.44	5.71
	B75	7.26	7.48	7.69	7.78	8.62	9.01
D30	B5	0.56	0.77	0.93	1.05	1.81	2.53
	B20	1.08	1.28	1.44	1.52	2.28	2.91
	B50	2.28	2.51	2.65	2.77	3.59	4.4
	B75	3.58	3.87	3.96	4.25	5.11	6.29
D40	B5	0.5	0.74	0.9	1.05	1.87	2.57
	B20	0.7	0.96	1.1	1.25	2.01	2.7
	B50	1.3	1.56	1.68	1.82	2.58	3.29
	B75	1.92	2.19	2.34	2.49	3.3	4.06

Stability N^2

		T2	T3	T4	T5	T8	T15
D20	B5	1.15	1.27	1.4	1.59	1.98	2.61
	B20	1.27	1.39	1.53	1.72	2.11	2.75
	B50	1.52	1.65	1.8	2	2.39	3.05
	B75	1.71	1.84	2.03	2.22	2.82	3.27
D30	B5	1.14	1.27	1.4	1.59	2.02	2.78
	B20	1.21	1.34	1.47	1.67	2.1	2.9
	B50	1.33	1.46	1.59	1.8	2.25	3.1
	B75	1.4	1.54	1.68	1.88	2.34	3.25
D40	B5	1.14	1.27	1.4	1.59	2.03	2.8
	B20	1.17	1.3	1.43	1.63	2.07	2.85
	B50	1.23	1.36	1.49	1.69	2.14	2.92
	B75	1.27	1.4	1.57	1.74	2.2	2.98

Epilimnion Temperature

		T2	T3	T4	T5	T8	T15
D20	B5	0.05	0.08	0.12	0.16	0.49	1.62
	B20	0.06	0.1	0.13	0.18	0.5	1.64
	B50	0.06	0.1	0.13	0.18	0.53	1.76
	B75	0.06	0.09	0.13	0.18	0.53	1.75
D30	B5	0.05	0.08	0.12	0.16	0.47	1.6
	B20	0.05	0.08	0.12	0.17	0.48	1.6
	B50	0.05	0.08	0.12	0.17	0.48	1.64
	B75	0.05	0.08	0.12	0.17	0.48	1.64
D40	B5	0.05	0.08	0.11	0.16	0.47	1.6
	B20	0.05	0.08	0.11	0.16	0.47	1.6
	B50	0.05	0.08	0.12	0.16	0.47	1.6
	B75	0.05	0.08	0.12	0.16	0.47	1.6

Figure 9: Coloured checkboard of the effects of vertical resolution effects on three lake thermal properties. The x-axis represents the resolution in the Top layer T [m]. The y-axis indicates the resolution in the Bottom layer B [m] and the depth D [m], separating the two layers T and B (see Figure 8 for the definitions of B, T and D). The three studied parameters presented in the top x-axis are the position of the thermocline, the maximum stability N^2 and the mean epilimnion temperature. The value of the mean difference compared to the reference 1-m resolution is indicated for each case in meters for the thermocline position, as a factor for the stability N^2 and in °C for the epilimnion mean temperature. The colour scale indicates if the value is accurate (green), acceptable (orange) or unacceptable (red) according to specific thresholds presented above.

There is a strong relation between the resolution in the top layer and the accuracy of the results (Figure 9). Indeed, the accuracy decreases for each parameter when the resolution in the top layer decreases, independently of the resolution in the bottom layer. For instance, the calculated epilimnion mean temperature difference with the 1-m resolution increases from 0.05 °C (green) with a resolution of 2-m in the top layer (T2) to at least 1.6 °C (red) with a resolution of 15-m in the top layer (T15).

The depth D separating the two layers plays an important role for the position of the thermocline and the stability N^2. The two boxes at the bottom, where D is equal to 30 and 40 m, respectively, are quite similar, whereas the accuracy is much worse for the top block where D is equal to 20 meters. The depth D is not important for estimating the epilimnion mean temperature, which is not surprising as the epilimnion is the top layer of the lake, usually not very deep and hence not influenced by the resolution in the bottom layer as well as the depth D.

The resolution in the bottom layer does not play an important role in the accuracy of the results for all analysed parameters, provided that D is at least 30 m. A higher resolution in the bottom layer would be required in order to monitor the depth of seasonal mixing in winter which was not included in the analysis here. The winter mixing depth is important for the recycling of nutrients and the replenishment of oxygen to the deep water (section 2.4). It can, however, also be estimated with good accuracy from profiles of temperature and oxygen concentrations as they are measured in current water quality monitoring programs. The continuous measurements proposed here would in addition allow an accurate observation of the timing of this deep mixing.

4.2.2 Recommendations

Based on the vertical analysis presented above, we suggest that it is important to **monitor the entire water column**. As presented in the results, it is desirable to have a high vertical resolution in the top layer to analyse short-term effects of the meteorological forcing and the corresponding responses of the lake. **The distance between sampling depths in this top layer should not exceed 5 meters.** This is the maximum distance to obtain representative results for all the characteristics presented in Figure 9. If the distance between sampling points exceeds 5 m, the epilimnion mean temperature, the maximum stability and the thermocline depth cannot be determined with sufficient accuracy. A resolution of 3 or 4 m would be preferable, and higher resolutions would be optimal.

The depth separating the top and the bottom layer affects the accuracy of the parameters if not well chosen. It should be located below the lower end of the thermocline throughout the stratified season. This depth will depend on the characteristics of a lake (maximum depth, size, wind exposure, trophic condition, etc.). For Lake Zurich, the analysis shows that the **depth separating the two layers should be around 30 meters,** in order to accurately monitor the thermocline depth. This value is likely a good choice for most larger lakes in Switzerland.

The bottom layer resolution does not have strong effects on the accuracy of the studied parameters, which makes sense as changes of temperature in the deep water are not high (Livingstone and Lotter 1998). Hence, the **bottom resolution can be coarse**; a measurement every 50 m should be enough to characterize the seasonal variations. However, the bottom temperature should always be monitored to quantify and understand winter mixing processes. In addition, a higher resolution would be required for monitoring the maximum depth of mixing in winter.

Results of the survey indicate that 94 % of the concerned people think that monitoring the entire water column is very important and 6 % think this is fairly important. The preferred vertical resolution of the survey participants varies between every 0.1 m to every 2 m.

4.3 TEMPORAL RESOLUTION

4.3.1 Results

As presented above, lake temperatures in Switzerland are currently monitored by measuring vertical temperature profiles at a monthly or bi-monthly interval. Figure 10 displays time series of surface and bottom temperature with a time indication of such a monitoring frequency.

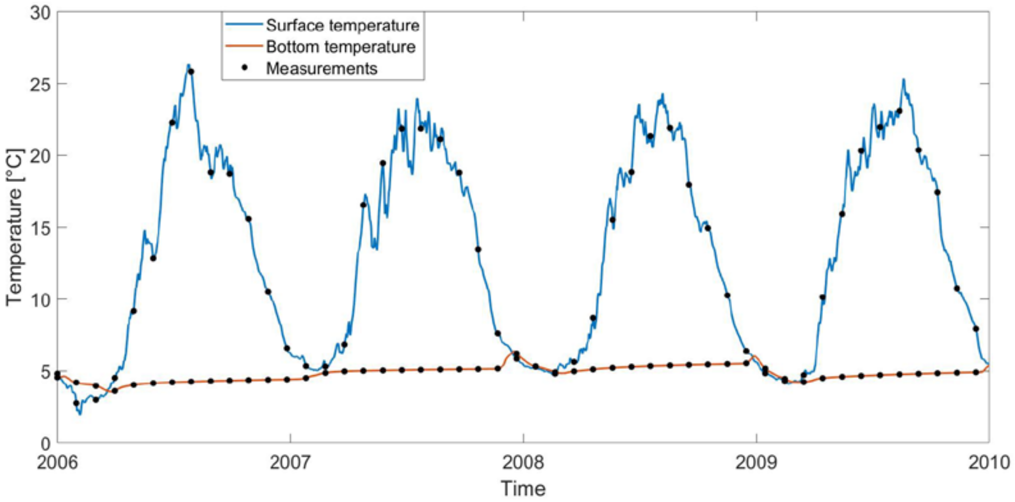


Figure 10: Time series of the surface (blue line) and bottom (red line) temperature from 01.01.2006 to 01.01.2010 in Lake Zurich. Black dots indicate the timing of measurements that would have been performed every 30 days (monthly measurements). Data were obtained from Schmid and Köster (2016).

Figure 10 shows the high variability of the surface temperature, while the bottom temperature is, as explained above, changing much more slowly. Figure 10 clearly shows that monthly measurements are not sufficient to precisely monitor the surface temperature. Indeed, some temperature fluctuations are completely missed, for instance during the summer 2007 or 2008. These measurements would have overestimated the mean summer surface temperature in 2007 and underestimated them in 2008. Moreover, fast processes (e.g., floods, storms…) can have significant impacts on lakes, especially in high altitude short retention time lakes (Perga et al. 2018), and are usually missed with the current monthly monitoring (Figure 11).

In the case described in Figure 11, storms affected the temperature and the oxygen concentration of the lake within the time scale of a day. Monthly observations would have shown the differences between the situation before and after the storm but would not have allowed to assess the processes that occurred in between. The impacts of storms or other fast events such as floods on the lake thermal structure can only be consistently interpreted with a high temporal resolution monitoring.

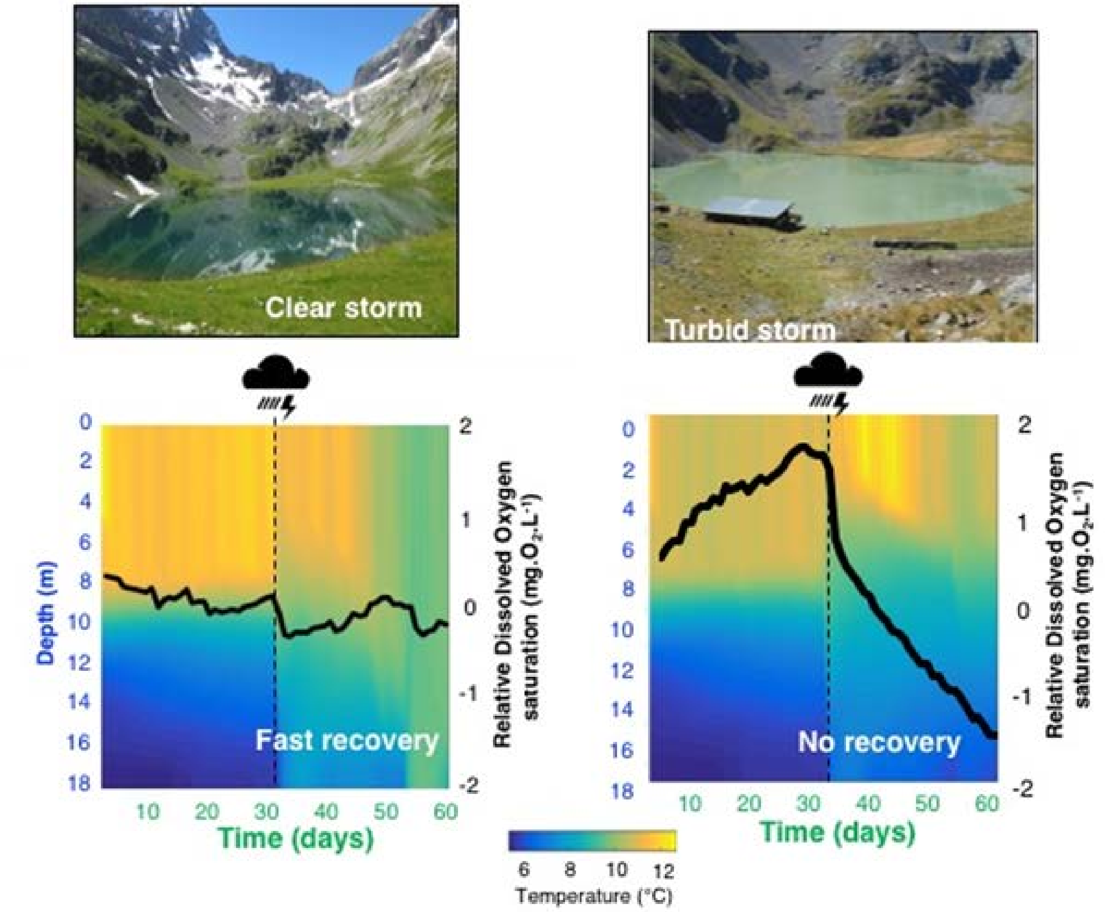


Figure 11: Example of short time scale event (storm) having a long time (seasonal) effect on temperature and biology in a small high altitude lake in the French Alps (Lake Muzelle). While the first storm (top and bottom left panels) had little effects on the thermal structure of the temperature and relative dissolved oxygen concentration in the lake, another storm (top and bottom right panels) durably affected both the thermal structure and the oxygen content. The strong effect was due to the high particle loads associated with the storm. The occurrence of the observed turbid storms was not related to the wind or rain intensities during the events. Instead, the turbid storms occurred after dry and atypically warm spells, i.e., meteorological conditions expected to be more frequent in this alpine region in the upcoming decades. Consequently, storm events, notwithstanding their intensity, are expected to strongly imprint the future ecological status of alpine lakes under climate warming. Figures from Perga et al. (2018).

Temperature trends are one of the most often used measure for assessing the effects of climate change on the thermal properties of lakes. Figure 12 shows the variation that is induced in estimations of surface and bottom water temperature trends from sampling at different intervals. The results clearly indicate that monthly sampling does not allow an accurate estimate of the temperature trend. For example, for the month of July, the true surface trend is 0.36 °C decade^{-1}, which is a typical observed trend for Central European lakes (Woolway et al. 2017). Monthly sampling would result in an estimated trend anywhere between 0.00 and 0.89 °C decade^{-1} and with 10 % probability even outside these margins. Even for weekly sampling, the 90 % interval for the estimated trends lies between 0.31 °C decade^{-1} and 0.59 °C decade^{-1}, i.e. an overestimation of the trend by 66 % is well possible. The annual temperature trend of 0.39 °C decade^{-1} can be estimated within a range of approximately ±10 % with weekly sampling and ±35 % with monthly measurements. These results clearly show that high temporal resolution is required to accurately estimate lake surface temperature trends, even for a comparably long dataset of 33 years.

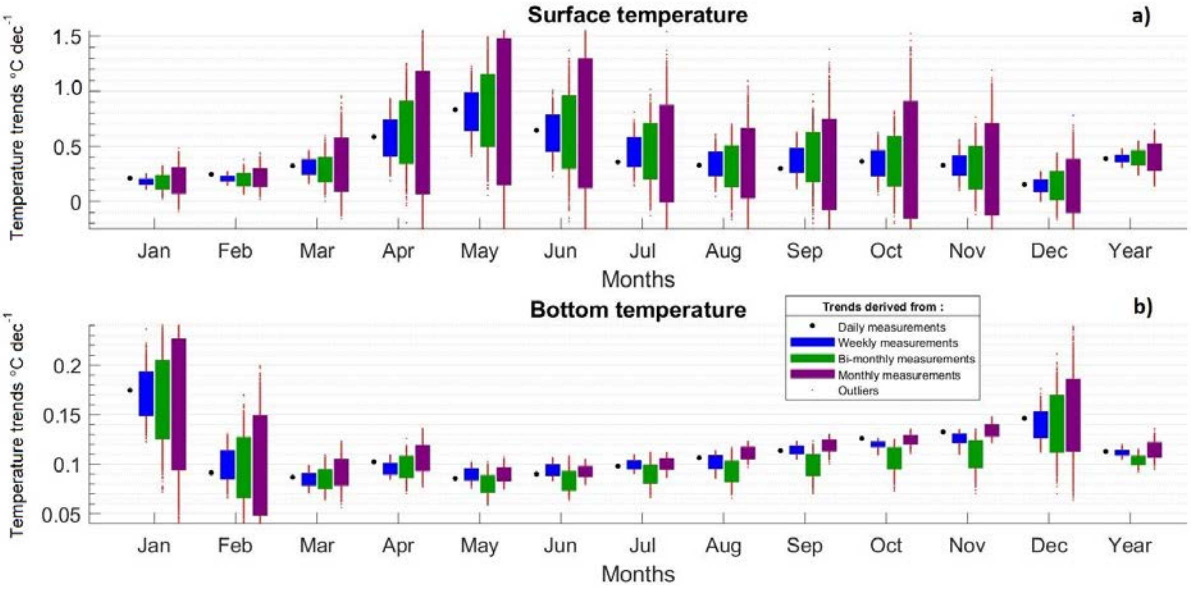


Figure 12: Monthly trends of lake a) surface and b) bottom temperature [°C decade^{-1}] calculated from 33 years of simulated temperatures sampled at different temporal resolutions. Black dots represent trends calculated from daily measurements. Every coloured box represents the 90 % spread of Monte Carlo simulation results (from quantile 0.05 to 0.95) for different measurement resolutions. Blue represents weekly measurements, green bi-monthly measurements and purple monthly measurements. Red dots are the outliers for each month (below 0.05 quantile and above 0.95 quantiles). Note that some outliers are not shown because of the scaling of the graph.

Bottom temperature trends are less sensitive to the measurement time resolution because of their smaller temporal variation, except during the winter months, when seasonal mixing can induce short temperature peaks. These bottom temperature peaks are, however, not necessarily very reliably reproduced by the model used here, so these values should be considered with care.

Besides the sampling frequency, also the length of the available dataset plays an important role for detecting temperature trends. The reason for this is that the time series effectively consists of a combination of a (not necessarily linear) trend and an interannual random variation that is larger than the integrated trend over time scales of one to a few decades. This interannual random variation is further increased by the random variation induced by a low sampling frequency.

To assess the effect of the length of a time series, we quantified both sources of uncertainty with bootstrapping based on simulated time series of different length of surface water temperature from Lake Zurich starting in 1981. The results are presented in Figure 13.

The black line indicates the one-sided 90 % confidence interval for the estimated trend, based on a dataset of daily measurements. Since the trend calculated from the daily dataset should almost perfectly agree with the real trend that occurred in the lake, this line mainly quantifies the uncertainty of the estimated linear trend that results from the interannual meteorological variation. The difference between the coloured lines and the black line then indicates the additional uncertainty that is created by the reduced sampling frequencies.

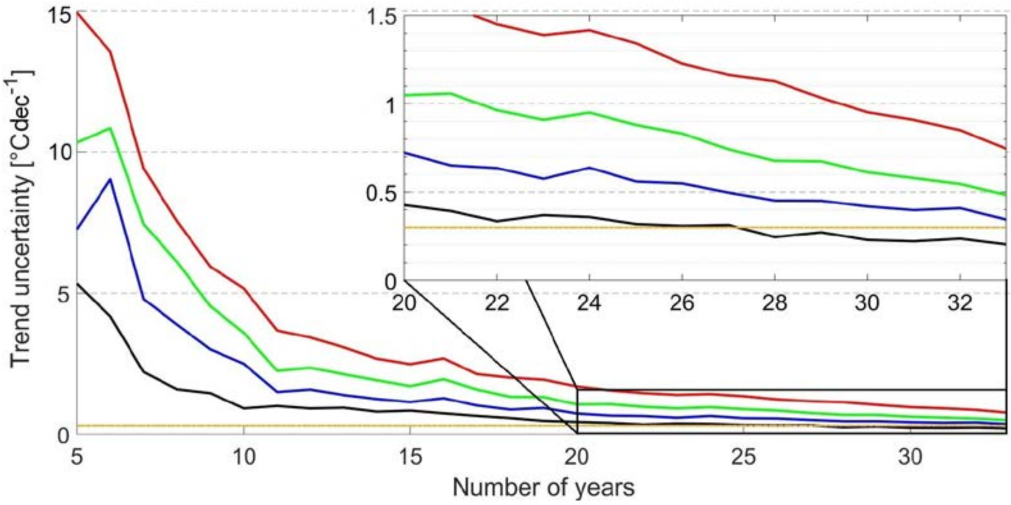


Figure 13: Summer (July to September) trend uncertainty [°C decade^{-1}] according to the length of the available time series. Uncertainties represent the difference from the mean of the 90% bootstrap confidence intervals, i.e. the true value of the trend is expected to lie with 90 % probability within the calculated mean trend ± the value shown in the figure above. Different temporal resolutions are indicated by the colours: black indicates daily measurements, blue weekly, green bi-monthly and red monthly measurements. The period from 20 to 33 years is highlighted and presented in the zoom in the top-right of the graph. The dashed yellow line indicates a threshold of 0.3 °C decade^{-1} for the trend uncertainty. The calculated trends are based on temperatures simulated by Schmid and Köster (2016).

The results highlight the importance of long data-sets for accurately quantifying temperature trends caused by climate change. Indeed, the uncertainty is high if the length of the dataset (total period covered) is small, even with daily measurements. For instance, for a typical temperature trend of 0.3 °C decade^{-1} indicated by the dashed yellow line, daily observations over almost 30 years duration are already required in order to observe a positive trend with 95% confidence. This is the case if the uncertainty presented in Figure 13 becomes smaller than the mean value of the observed trend. Compared to this, for the case of Lake Zurich, the calculated uncertainties still range from 0.35 °C decade^{-1} for weekly measurements to 0.75 °C decade^{-1} for monthly measurements after 33 years of monitoring. This implies that sampling at lower frequency requires longer measurement records to achieve the same robustness for estimated trends. High sampling frequency is therefore indispensable for early detection of changes.

Figure 14 is another example of the high variability that low measurement frequency induces to estimated trends. In this case, trends of the duration of stratification are presented and results show an extreme variability with temporal resolution. The median (red line of the boxplots) is always relatively close to the real trend which is due to the high number of iterations (10'000). However, the variability is important to note here as it represents the interval within a trend would be estimated with 90% probability from random measurements.

Indeed the trend estimated from weekly measurements ranges between 1.4 and 3.8 days per decade (90 %-confidence interval), compared to the real trend of 2.4 days per decade. Monthly measurements are likely to completely miss the real trend with a confidence interval -1.7 to 8.2 days per decade.

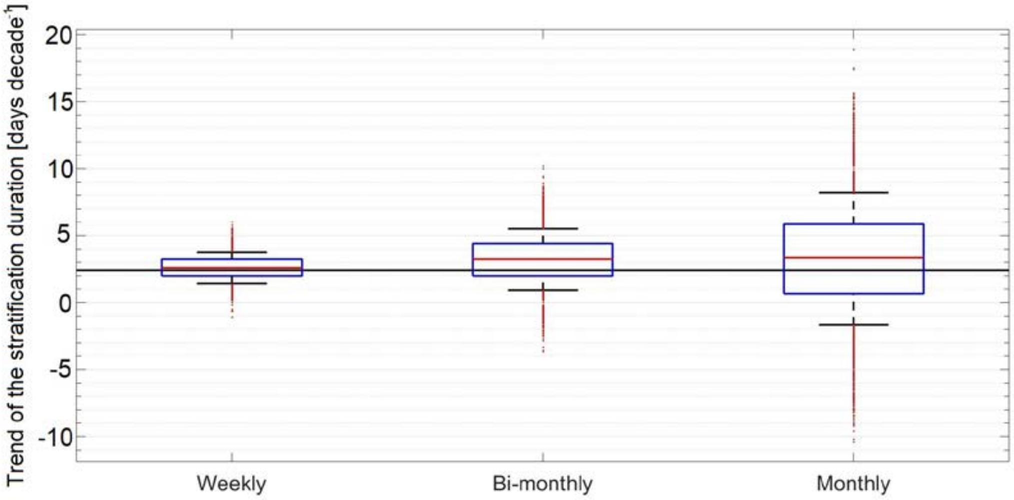


Figure 14: Boxplots of trends of the duration of stratification calculated from to three different temporal sampling resolutions presented in the x-axis. The black line represents the real trend obtained with daily measurements. In each boxplot obtained by a Monte Carlo analysis, the red line represents the median, the box lines represent the 25th and 75th quantiles, the error bars represent +/–1.28 σ (90 %-confidence interval) and the red points are the outliers.

Trends regarding the mixing duration have shown an even higher variability, explained by the shorter period of the mixing, which causes extreme differences between the measurement frequencies (Appendix 10.3). Other studies have also been performed regarding heat content and all showed similar results, with a high uncertainty with smaller temporal resolution. Results are presented in Appendix 10.3.

4.3.2 Recommendations

For estimating **long-term trends** of thermal regimes, a **daily measurement interval is recommended**. As shown above, the uncertainty of estimated trends rapidly increases with decreasing measurement frequency. For monthly measurements and time series of several decades, the confidence intervals are in many cases significantly larger than the observed trends, and these trends can therefore not be determined with statistical significance. However, for monitoring programs it is generally not realistic to sample with daily resolution (or even weekly resolution) from a boat. Moreover, even if sampling from boats were performed at a high rate, the observations would likely be biased as sampling may be impossible under harsh meteorological conditions. Therefore, given the required minimum weekly or daily sampling period, the only practical solution consists in using **moorings with temperature loggers**. Once a mooring is installed, sampling frequency is not an issue and could be reduced to hourly or 10 min resolution with no significant additional costs. This high temporal resolution will provide additional opportunities to study rapid effects of storms, floods or differences between days and nights.

Results of the survey concerning the temporal resolution indicate that 54 % of the concerned people think that an optimum temporal resolution would be hourly measurements, 31 % voted for daily measurements and 15 % for weekly measurements. 25 % think hourly measurements is the minimum resolution, 31% voted for daily measurements, 19 % for weekly measurements and 25 % for bi-monthly measurements as minimum resolution.

4.4 GENERAL CONCLUSIONS AND RECOMMENDATIONS

The current standard monitoring method of measuring vertical profiles at a monthly frequency yielded extremely valuable datasets from many lakes, which have been very useful for improving our understanding of processes occurring in lakes, for environmental assessment in the process of eutrophication and re-oligotrophication, and for designing management strategies. Nevertheless, the calculations presented above clearly indicate that this method is not sufficient for monitoring and early detecting changes in the thermal properties of a lake resulting from climate change or from other anthropogenic thermal alterations. For this purpose, **measurements should be performed daily**. Since daily measurements from a boat are cost- and labour-intensive, the most effective way of acquiring data with a high resolution is the **installation of a mooring**. A mooring is a floating buoy that supports real-time monitoring instruments such as sensors and data loggers. In the case of temperature, a thermistor string, or thermistor chain, is a series of thermistors embedded along a single cable from the surface to the bottom of the lake. Moored instruments have the advantages of **high temporal resolution**. Indeed, monitoring can be effectuated with a high frequency and can cover daily fluctuations and response to major meteorological events (e.g. storms). Moreover, as moored buoys are at fixed locations, they provide long time-series of data from a constant location, which is important for understanding climate effects. Data can either be communicated in near real time using cell phone communication or LoRa (long range wide area network) wireless technology, or retrieved annually to bi-annually during maintenance of the mooring. Finally, higher temporal resolution (i.e. every 10 minutes) would allow the study of fast processes (i.e. floods, storms, etc…) and their effects on lakes. As presented above, they are usually missed with the current monitoring, but can have a strong influence on the thermal structure of lakes, especially in high altitude short retention time lakes (Perga et al. 2018).

In summary, based on the analysis above, we think that **water temperature in lakes should be monitored at least every day, with a high spatial resolution (at least every 5 meters) in the top 30 meters, and with a smaller resolution below. We therefore recommend installing moorings that can provide such resolutions.**

Besides that, **we also recommend to continue the currently existing measurements of high-resolution vertical temperature profiles** accompanying water quality monitoring. Compared to the effort for chemical and biological water quality measurements, the additional effort for collecting a temperature profile is small, but these profiles can still yield additional information about the vertical temperature structure (e.g. the exact depth of seasonal winter mixing) which can be complimentary to the data acquired with moorings.

5 MONITORING NETWORK

5.1 SELECTION OF MEASUREMENT LOCATION WITHIN A LAKE

A **mooring** for continuous temperature measurements is ideally located at the **deepest point of a lake**. This point is typically representative for the entire lake in small lakes. In large lakes, circulation patterns and spatially variable meteorological forcing can create significant spatial temperature heterogeneities, and measurements at a single location can lack representativeness. This point was not investigated in this report and we only list a few processes that can lead to spatial variability: upwelling, downwelling, gyres, faster heating or cooling of shallow nearshore areas. In large lakes, the representativeness of monitoring stations should be assessed ideally with a combination of remote sensing data (Kiefer et al. 2015) and three-dimensional hydrodynamic models (Bouffard et al. 2018). Some precautions need to be taken for other lakes with several sub-basins presenting different characteristics (e.g., the meromictic North-basin and the holomictic South basin of Lake Lugano, or the different basins of Lake Lucerne). In these cases, monitoring of each basin may be indicated as the temperature can vary significantly between lakes, as has been shown for the monthly temperature profiles from different basins of Lake Lugano (Lepori and Roberts 2015).

Besides this, the following points need to be considered when selecting a measurement location within the lake:

- **Avoid local effects of inflows:** Locations near major river inflows or known groundwater inflows should be avoided, as these are not representative for the lake as a whole.
- **Minimum disturbance of other users of the lake**, including ship traffic, fisheries and recreational activities.
- **Maximize distance to the shores**: Monitoring near-shore temperatures would be interesting from a research point of view, as they might allow to better understand internal waves and transport processes between the near-shore and the open areas of a lake. But near-shore locations cannot be considered as representative for a lake and are therefore not indicated for monitoring the lake as a whole. However, **specific near-shore temperature monitoring may be considered to assess climate change effects on protected littoral areas**.

5.2 LAKES IN SWITZERLAND

There is **no single clear definition of a lake**. In general, a lake is a body of standing water. Lakes are distinguished from rivers by the flow speed or retention time, but there is a smooth transition between wide river stretches or oxbow lakes and lakes. Furthermore, numerous different approaches have been proposed to separate lakes from ponds by either size or depth (e.g.,Oertli et al. (2005)), but none of them has proved to be convincing for all cases. Finally, lakes are separated from reservoirs, where the former are of natural origin and the latter are man-made. Again, the separation is not always clear, as some natural lakes have been artificially increased, and some natural lakes are used as reservoirs for hydropower production or water supply, resulting in artificial lake level fluctuations.

According to a GIS evaluation of FOEN based on the maps of Swisstopo, Switzerland contains 1592 lakes and reservoirs larger than 0.5 ha with a total area of 1422 km^2, covering about 3.5% of the area of Switzerland (Schubarth and Weibel 2009; Swisstopo 2016). Without exception, **all large lakes in Switzerland are deep lakes** which are thermally stratified in summer. This is due to the mountainous topography of Switzerland, and is not representative of the worldwide lake distribution, where the vast majority of lakes are shallow lakes (Messager et al. 2016). As a consequence, it is difficult to infer results from other place in the world when it comes to Swiss lakes. Nowadays, most **natural Swiss lakes larger than 5 km^2 are monitored with regular temperature profiles** by the cantonal agencies or international commissions. Temperature profiles in smaller lakes are only collected regularly in specific cases, when it is typically requested to follow a water quality problem as, for instance, eutrophication or oxygen deficits. Otherwise, temperature profiles are usually collected at larger intervals in smaller lakes, and often restricted on the summer season.

5.3 CRITERIA FOR SELECTING MONITORING SITES

It is hopeless to monitor with in-situ observations the thermal structure of all lakes in Switzerland. Note, however, that this objective could potentially be reached in the future through **an integration of in-situ measurements, remote sensing observations, and hydrodynamic models** (e.g., simstrat.eawag.ch). However, it is important to know that **lakes are reacting differently to climate change** as the **temperature is influenced by many parameters**, presented below.

5.3.1 Altitude

The lake thermal structure changes with altitude. Lakes in the Swiss Alps respond to climate forcing according to two distinct altitudinal thermal regimes (Livingstone et al. 2005). The altitude threshold separating the two different regimes is located around 2000 m. Within the low-altitude regime, lake surface water temperatures are strongly related to air temperature and altitude. On crossing the threshold to the high-altitude regime, the relationship of lake surface temperature to both altitude and air temperature weakens considerably. At high altitudes, lakes are usually dimictic. They get inversely stratified and eventually ice covered in winter which in turn affects the correlation between air temperature and lake surface water temperature. During summer, high-altitude lakes are often weakly stratified with a thick mixed layer, compared to the stably stratified lakes in low-altitude regimes. Moreover, inflowing meltwater from snow in the catchment area results in a strengthening of the inverse stratification or an upward displacement of the thermocline in the high-altitude regime, whereas lakes in the low-altitude regime are unaffected by meltwater. This altitude threshold will likely change as well with the climate change.

Furthermore, it is now recognized worldwide that the rate of warming air temperature is amplified with elevation. Climate change affects more strongly high mountain environments that experience more rapid changes in temperature than environments at lower elevations (Pepin et al. 2015). These stronger changes will probably lead to different impacts on lakes at high altitudes than low-altitude lakes.

Finally, high-altitude lakes are generally small with a strongly fluctuating retention time (see below). The connection between the watershed and high altitude lakes is also expected to change in the future due to a change in the distribution of rainfall and dry periods (Perga et al. 2018) and a change in the volume and timing of accumulated winter snow (Sadro et al. 2018).

5.3.2 Size

Several studies have shown that the response of deep water temperatures and thermal stratification depends on lake size and morphometry (Kraemer et al. 2015; Winslow et al. 2015). Moreover, small lakes are usually more wind-sheltered than large lakes and do not allow the full build-up of waves. As a consequence, the contribution of wind to mixing is less important, resulting in a different thermal structure in the lake (Winslow et al. 2015).

5.3.3 Depth

Morphometry is an important factor determining a lake's reaction to climate change, and the depth is one key parameter (Winslow et al. 2015). Kraemer et al. (2015) have shown that deep lakes have experienced larger changes in lake stratification than shallower lakes in the same time period.

5.3.4 Turbidity/light penetration

Light penetration controls the vertical extent that is warmed by absorption of solar radiation. In clear lakes, the solar light reaches deep layers, whereas in turbid lakes, it is absorbed in the first meters. In this second case, surface layers will be warmer with a shallower thermocline, with corresponding impacts on thermal stratification and productivity (Schindler 1997; Snucins and John 2000). Light penetration and turbidity are changing in time and are typically affected by the trophic state of the lake, organic matter and river inputs. Lake transparency is expected to be affected by climate change and the resulting alterations in a lake's catchment (Rose et al. 2016).

5.3.5 Residence time

The residence time is the average time that water spends in a particular lake. It is often calculated as the ratio between the volume of the lake and the total inflow (precipitation, river input and sub-aquatic inflows). The residence time can indicate how strongly and quickly a lake will react to changes in the watershed.

5.3.6 Mixing regime

Mixing regimes were already described in section 2.4. In Appendix 10.5, Figure A.7 represents the regimes of the largest natural lakes in Switzerland according to their altitude and average depths.

5.3.7 Anthropogenic impacts

Anthropogenic impacts, such as heat disposal to inland waters, influence water temperature. In case of extensive usage, they can also affect stratification, heat and nutrient fluxes, deep water renewal, and biota (Gaudard et al. 2018),as it is currently the case in Lake Biel due to the heat input from a nuclear power plant (Råman Vinnå et al. 2017).

5.3.8 Local climate

Climate change in Switzerland is expected vary regionally (Fischer et al. 2012). This will lead to different responses from lakes according to the local climate. The two main climate regions in Switzerland are north and south of the Alps. In the last technical report from NCCS regarding climate change in Switzerland, the country was divided in five different parts (North-East, West, South, Alpine East and Alpine West), and results indicated differences according to the location (NCCS 2018).

5.3.9 Ground water exchanges

Little is known about groundwater exchanges in Swiss lakes. However, we assume that they should be not very relevant for lake temperature in most cases. There are probably exceptions from this rule.

5.4 CHOICE OF LAKES FOR A MONITORING NETWORK

Ideally, the lakes included in a monitoring network would provide the **full combination of the main parameters influencing temperature in lakes** mentioned above. However, this is likely not possible with the resources available for the creation of a monitoring system. Therefore, **four scenarios are proposed** for the choice of lakes included in the temperature monitoring program. They are presented in section 6.

Results of the **survey** indicate that more than 80 % of the considered people would be interested in additionally monitoring small lakes. 80 % of survey respondents think that it is very important to choose lakes with **different mixing regimes**, 79 % lakes at **different altitudes** and 81 % lakes with **different depths**. Monitoring lakes with different volumes, surface area and residence times was considered as very important by more than 50 % of survey respondents. Turbidity, anthropogenic impacts, local climate and ground water exchanges were considered less important (<50 %).

6 SCENARIOS FOR A LAKE MONITORING NETWORK

6.1 INTRODUCTION

In the following, we present four different basic scenarios for a lake temperature monitoring network in Switzerland. These are not exclusive, which means that also a combination of different scenarios or an intermediate between two scenarios is possible. For the moment, only the basic properties of the scenarios are presented, the selection of specific lakes needs to be further developed once a decision has been made on the extent and the focus of the monitoring system.

6.2 FIRST SCENARIO - STATUS QUO

The first scenario is based on the status quo of the current monitoring combined with modelling approaches. In this scenario, the monitoring will be continued as done today, with no further temperature measurements added. However, modelling approaches should be implemented and developed as a means for interpolating between observations. A description of the aspects of a modelling approach is provided in Section 7.2.

Temperature measurements are already performed in most of the largest lakes of Switzerland, as presented in section 3. Yet, the spatial and temporal resolution is clearly insufficient for tomorrow’s challenges. Based on these measurements and on meteorological data, modelling of the entire water body can be done for some lakes and will give information on the thermal structure, and on vertical, horizontal and temporal variabilities.

This first scenario will provide temperature modelled data for lakes that are already monitored. This includes mostly the largest lakes of Switzerland

However, the validation of the models needs high-quality measurements to avoid strong bias, and if no measurements are added, the accuracy of the models will be limited. Moreover, small lakes will not be included in this monitoring system, and it will not be possible to assess the effect of climate change on lakes at higher altitudes. For this scenario to be successful it is anyway needed to setup a short (< 5 years) monitoring campaign in each lake to provide enough data for model calibration and validation.

The obvious advantage of this method are the low costs. The major drawback is that lake thermal dynamics can be only evaluated through loosely validated numerical models

6.3 SECOND SCENARIO - LARGEST LAKES

The second scenario is based on monitoring only the largest lakes in Switzerland. These lakes have already a long history of low frequency temperature monitoring and are of national importance as they all play a major role in the local economy as well as for recreation.

The lakes can be chosen based on their sizes. For instance, by selecting the 17 lakes with a surface area larger than 10 km^2, or the 23 lakes with a surface area larger than 5 km^2, or in a larger perspective by selecting the 37 lakes with a size larger than 2 km^2. Figure 15 is a representation of the lakes that could be selected based on a size criteria.

Compared to the present monitoring, this scenario will provide additional information on the reaction of a lake's thermal structure due to climate change, and will allow a better quantification of trends in temperature and the duration and strength of thermal stratification. It includes lakes in both major climate regions (north and south of the Alps). It will also allow a more thorough validation of numerical models for the temperature of large lakes to support a broader analysis.

However, the largest lakes of Switzerland present some similar characteristics. They are almost all located on the Swiss Plateau, except for some lakes in Ticino. They are all deep lakes. Hence, monitoring only the largest lakes will not give any information about the effects of climate change on different altitudes, sizes, land uses and depths. Although directly relevant for most of the population living close to the large lakes, this second scenario will miss the global goal of understanding and correctly monitoring the entire water cycle from the small lakes close to the glaciers to the large peri-alpine lakes.

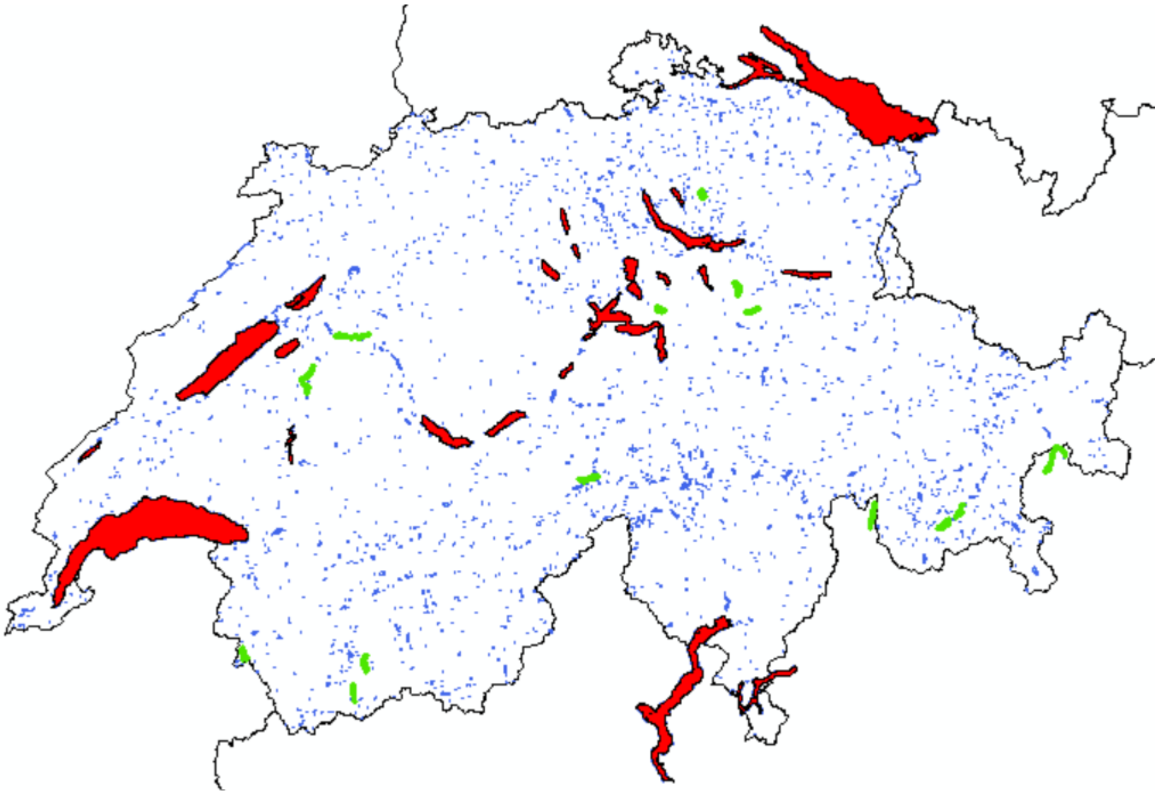


Figure 15: Map of Switzerland with indication of the selected lakes. Lakes larger than 5 km^2 are represented in red, those larger than 2 km^2 but smaller than 5 km^2 in green (increased in size to highlight them). All lakes smaller than 2 km^2 are plotted in dark blue. Data provided by Swisstopo (2016) Vector200, Bundesamt für Landestopographie (Art.30 Geo IV): 5704 000 000, reproduced by permission of swisstopo / JA100119.

6.4 THIRD SCENARIO - ALTITUDE GRADIENT

The third scenario is based on monitoring lakes with an altitude gradient by selecting several lakes which are located at different altitudes. Given the alpine nature of Switzerland, the fate of lakes at all altitudes is an important national aspect to consider. Moreover, data to assess the effects of climate change on smaller lakes is generally lacking at the Swiss and world level and little is known about those systems. It is hence difficult to foresee how to address the questions of tomorrow without understanding the situation of today. Selecting lakes following an altitudinal gradient will include small lakes, increasing the knowledge of the effects of climate change on these lakes.

One possible way to go would be to select lakes at a specific interval (e.g., every 100 or 200 m) in the altitude range between 200 m and 3000 m a.s.l. It remains to be discussed whether the lakes should be chosen to be relatively homogenous concerning the other criteria mentioned above, in order to avoid other effects disturbing the analysis of the effects of the altitudinal gradient, or whether they should include a range of qualitatively different lakes. However, if the number of studied lakes is limited, they should present at least similar trophic conditions, as otherwise the effects of different trophic conditions might mask the altitude effects.

Besides that, the selection of the lakes should be based on a discussion between FOEN and the cantons. Lakes should be excluded if there are any known plans for significant alterations within the lake or the catchment that are likely to affect lake temperature (such as land use change, forest growth, heat usage, water abstractions, or hydropower usage).

The third scenario will provide information on the effects of climate change on lakes at different altitudes, which is a high concern in Switzerland due to the unique topography. Ideally this plan would be complemented with a modelling strategy.

6.5 FOURTH SCENARIO - HIGH VARIABILITY

The last scenario would include the monitoring of many lakes, covering the entire range of characteristics influencing their response to climate change. It would include lakes from scenario 2 and 3 but also other lakes with different depths, trophic conditions, mixing regimes, land use, etc. The total number of lakes considered is estimated to be around 50.

This scenario will be the most complete to assess the impacts of climate change on lakes, as it is based on all the major characteristics that affect a lake's response to the modified forcing.

6.6 FINAL REMARKS

Scenario 1 will not bring any new *in-situ* measurements, hence it should be implemented with another scenario to be really efficient, or viewed as a complement to the monitoring. Scenario 2 and 3 are both very useful but they miss some important characteristics (altitude for scenario 2 and depth/size for scenario 3). Scenario 4 is, by far, the most complete, but also the most expensive.

The **ideal monitoring will be the combination of all the scenarios**, allowing a complete monitoring of the temperature and all the parameters describing it, and covering the entire range of characteristics altered by climate change, thus allowing an efficient modelling.

However, the initial costs of such a program would be high. Therefore, we recommend “iterative steps”. The monitoring could start with several lakes and be expanded step by step when needed and when possible. Alternatively, some lakes could be used as “pilot lakes” with a complete monitoring combined with other information (see section 7), thus allowing a smaller monitoring system in other lakes that can be installed iteratively.

Table 1 is an executive summary of the main advantages of each scenario. It shows what information can be gained from the different possible scenarios.

Scenario	Number of moorings	Advantages for climate change monitoring compared to current monitoring
1) Status quo	0	• High frequency modelled data (poorly calibrated).
2) Largest lakes	17 (> 10 km^2) 23 (> 5 km^2) 37 (> 2 km^2)	• Trends in lake surface temperature, duration of stratification, and other thermal properties of lakes can be better assessed. • High frequency modelled data fully calibrated for the largest lakes.
3) Altitudinal gradient	15 to 25 (depending on altitude resolution)	• Trends in lake surface temperature, duration of stratification, and other thermal properties of lakes can be better assessed. • Specific effects for alpine areas (with expected strong response to climate change) can be evaluated. • Effects of headwater lakes on rivers downstream can be assessed. • High frequency modelled data fully calibrated along an altitudinal gradient.
4) Representative lakes	~50	• Trends in lake surface temperature, duration of stratification, and other thermal properties of lakes can be better assessed. • Increased understanding how climate change effects are modulated by lake and catchment characteristics. • Extrapolation to non-monitored lakes based on their characteristics. • High frequency modelled data fully calibrated.

Table 1: Summary of the estimated number of moorings and advantages of each scenario.

7 COMBINATIONS WITH OTHER MEASUREMENTS AND METHODS

7.1 METEOROLOGICAL FORCING

For a detailed interpretation of observed temperatures in a lake, knowledge of the **meteorological forcing** is indispensable, as the heat fluxes across the air-water interface are the major driver for the thermal structure in a lake (Edinger et al. 1968). Monitoring the meteorological factors will give information on the forcing responsible of temperature changes, and is a basic requirement for a reliable forecasting. For many of the larger lakes, near-shore meteorological stations are already run by MeteoSwiss. For lakes that are not close to any of the current meterological stations, a basic meteorological monitoring could be designed, either near-shore or on the buoys of the moorings, preferentially in collaboration with MeteoSwiss.

According to the survey, 80 % of the respondents argue that a monitoring of some meteorological factors would be of a great interest to better understand the behaviour of lakes. 20 % think this is fairly important or important. They highlighted the importance of monitoring air temperature (air and wet bulb), wind speed, humidity, cloudiness, solar radiation, precipitation and air pressure, i.e., all parameters driving the heat exchanges. However, the most important parameter to monitor is probably wind speed, as it varies more strongly spatially than the other parameters, and because of its importance regarding the effects on vertical mixing in lakes (Ambrosetti and Barbanti 1999). Other parameters can be more easily interpolated between stations or taken from gridded datasets.

7.2 REMOTE SENSING AND MODELLING

In the attempt to improve the lake monitoring system of Swiss lakes, it is fundamental to link this to a broader reflexion on the integration of **remotely sensed** and **one- and three-dimensional models** into a lake monitoring system. An example of such integration for the cases of Lake Geneva, Lake Biel and Greifensee has recently been developed and is publicly available at meteolakes.ch (Figure 16). Provided that there is good in-situ data for calibrating and validating models, three-dimensional models can efficiently expand vertical measurements from a single location into a high spatial and temporal discretisation of the lake temperature. Models and satellite observations can also be used to assess the representativeness of existing in-situ monitoring stations and eventually help to define new or better locations (Kiefer et al. 2015). A well-established lake monitoring program will finally allow to model a large set of Swiss lakes and run sensitivity analysis and scenarios to assess a lake's response to climate change. We stress here that **neither models nor remotely sensed observation can replace in-situ observations but should be viewed as necessary additional tools for analysis**.

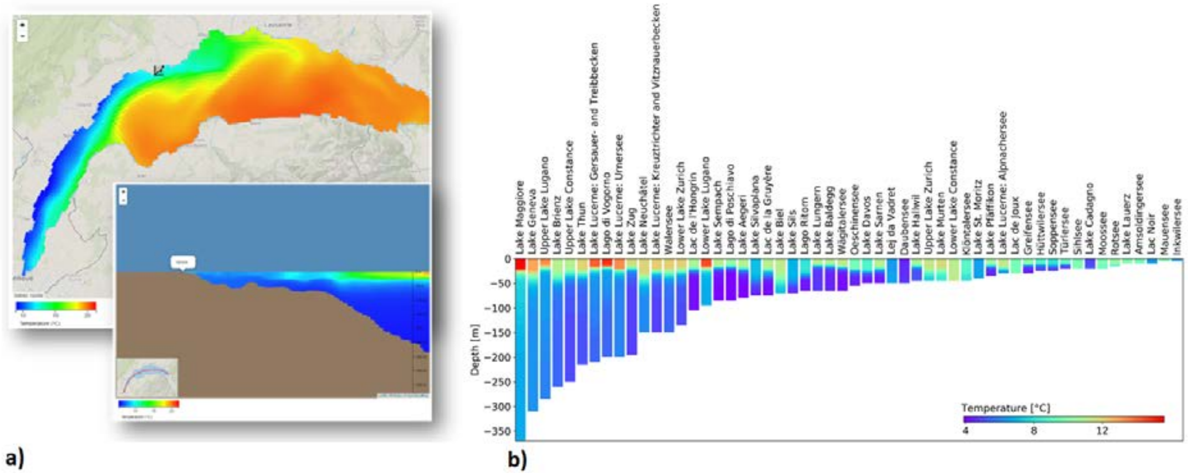


Figure 16: a) Example of results from a three-dimensional hydrodynamic model simulating the dynamics of lake temperatures on Lake Geneva (29.06.2017, meteolakes.ch). The figure shows an extreme example of temperature variability both spatially (top panel) and vertically (bottom panel). Note that the model could have been created only because of the high quality of the existing monitoring (Buchillon station – 1 measurement/minute). b) Vertical profiles of temperature in the largest lakes in Switzerland (28.11.2018, simstrat.eawag.ch). These temperature profiles were obtained by a 1-dimensional modelling approach.

Remote sensing and modelling will in any case be important additional activities for large lakes, as their size induces lateral variability that cannot be represented by only one measurement site in each lake.

According to the survey, 86 % of the concerned people think that coupling the monitoring program with hydrodynamic (1D or 3D) models would be interesting, varying from very (57 %) to fairly (7 %) useful or simply useful (22 %).

7.3 BIOCHEMICAL PARAMETERS AND WATER CHEMISTRY

Many parameters, such as the concentration of chlorophyll-a, or the occurrence of algal blooms, are directly related to the thermal structure of lakes. The absolute temperature plays a role, but the vertical structure is more important as it determines the vertical exchanges, crucial for phytoplankton growth. For instance, centric diatoms blooms are expected to occur less frequency if the mixing depth is reduced in winter (Yankova et al. 2017). Combined information on the thermal structure and biogeochemical parameters is hence crucial for interpreting climate change effects on biogeochemical processes and ecosystems in lakes.

The presence of a mooring for temperature monitoring in a lake also provides an opportunity for installing additional instruments for the monitoring of other water quality parameters, either for introducing new or complementing existing monitoring activities. Continuous measurements of **biochemical parameters** (e.g., chlorophyll-a, dissolved oxygen, total suspended solids or turbidity) and/or **water chemistry parameters** (e.g. pH, conductivity) could provide useful information to understand the biogeochemical processes occurring in lakes, such as the occurrence of algal blooms.

According to the survey, more than 86 % of the responding people think this would be important or very important, for both biochemical and water chemistry parameters.

8 DATA MANAGEMENT

8.1 OPEN ACCESS DATA PLATFORM

The **value of the monitoring data both for management and for scientific purposes is strongly increased if it is easily publicly accessible**. Currently, the cantonal monitoring data is generally made available by the cantons, in some cases on public platforms, or otherwise on request. However, the data is treated and stored differently by all agencies. Data analysis and especially studies comparing different lakes would be greatly facilitated if these data were stored in a common format on a joint data platform.

We therefore recommend to **collect both the cantonal monitoring data and the data from the new federal monitoring stations in a joint data platform**, including the already existing time series from previous monitoring. This could be organized in a similar way to the data platform for rivers (https://www.hydrodaten.admin.ch/).

Another example of an open access data platform is the **Global Environment Monitoring System for Water** and its database and information system GEMStat (GEMStat). The database contains data on ground and surface water quality from over 80 countries, thus providing an overview of water body conditions and the trends at global, regional and local levels. This is an extremely large dataset for the water quality parameters, but they often miss temperature measurements. Data are available through open-access.

Spontaneous comments by survey respondents also highlighted that data should be homogenised and stored in a shared database, which would facilitate their use. The unavailability of homogenous and freely available data was also one of the main criticisms of some existing temperature monitoring system in other countries.

8.2 DATA QUALITY CONTROL

Since the measurement of temperatures in lakes is more complex than for rivers, the quality control is also more demanding. The profiling data is usually quality-controlled by the local agencies which have long-term experience in assessing the data observed in their lakes. For the new high-resolution temperature measurements at national scale, **we propose to build up a two-step system for the quality control**. In a first step, the data should be analysed using **an automated quality control system**. In a second step, the data should be assessed once per year **by a scientific advisory committee**, who will be in charge of the analysis and validation of the quality of the data. Such an ad hoc committee will guarantee **a long-term commitment of the scientific community** that it is nearly impossible for individual scientists. Beside the quality control of the data, the committee could provide immediate feedback and recommendations regarding the observed changes which in the end will **facilitate dialog with different lake users**.

9 CONCLUSION

The temperature and the thermal structure of lakes is the key physical parameter directly related to all the other parameters (chemical and biological). Lakes are altered by climate change in many ways and the thermal structure is also strongly affected and will continue to change in the future. These changes can lead to significant alterations regarding lakes. In order to better understand and better predict the effects of climate change on lakes, a monitoring of the thermal structure of lakes is indicated.

In order to precisely describe the thermal structure, the monitoring of the entire water column at a high temporal resolution is needed. Moorings with thermistors are the indicated way of achieving this.

Lakes react differently to climate change depending on several characteristics. We proposed in this report four different scenarios for the lake network that could be considered in this monitoring program. Independent of the chosen scenario, it will be important to maintain a consistent and up-to-date lake monitoring program as a base for maintaining the excellent water quality of the beautiful and numerous Swiss lakes in a changing climate for the benefit of the Swiss population.

10 APPENDIX

10.1 LIST OF LAKES

Table A.1 contains the 38th largest basins (some lakes, i.e. Luzern or Lugano are divided in several basins when they present different characteristics) with some smaller artificial lakes. 40 basins in total with the following characteristics: type (N for natural, A for artificial), canton, volume (km^3), surface area (km^2), altitude (m asl), mean and max depth (m), residence time (days), catchment area (km^2), mixing regime and the trophic state, agencies in charge of the monitoring, and frequency of the measurements.

Name	Type	Canton	Volume	Surface area	Maximum depth	Average depth	Altitude	Residence time	Catchment area	Mixing regime	Trophic state	Who is monitoring?	Frequency	Comment
			km^3	km^2	m	m	m	day	km^2					
Lake Geneva	N	GE VD VS	89	580	309	154	372	4160	7975	Oligo	Eu	CIPEL and EPFL	Continuous and monthly to bi-monthly	Shared with France
Upper Lake Constance	N	SG TG	47.6	473	251	101	395	1570	11500	Oligo	Meso	IGKB	Monthly to bi-monthly	Shared with Austria and Germany
Lake Neuchâtel	N	NE BE FR VD	13.77	218.3	152	64	429	3000	2670	Mono	Meso	BENEFRI	Monthly	
Lake Maggiore	N	TI	37	212.5	372	177	193	1460	6600	Oligo	Oligo	CIPAIS	Monthly to bi-monthly	Shared with Italy
Lower Lake Zurich	N	SZ SG	3.36	68.2	136	51	406	510	1830	Mono	Meso	WVZ, AWEL, Limnological Station (UZH)	Monthly to bi-monthly	
Lower Lake Constance	N	TG SH	0.8	63	45	13	395	17	11500	Mono	Meso	IGKB	Monthly to bi-monthly	Shared with Germany
Lake Lucerne: Kreuztrichter and Vitznauerbecken	N	LU NW SZ	4.35	59	151	83	434	260	2124	Mono	Oligo	AKV	Monthly to bi-monthly	Subbasin
Lake Thun	N	BE	6.5	48.3	217	136	558	684	2500	Mono	Oligo	AWA	Monthly	
Lake Biel	N	BE NE	1.12	39.3	74	28	429	58	8305	Mono	Meso/Eu	BENEFRI	Monthly	
Lake Zug	N	ZG SZ LU	3.2	38.3	197	83	417	5370	204	Mero	Eu	AfU ZG	Monthly	
Lake Lucerne: Gersauer- and Treibbecken	N	LU NW SZ UR	4.41	30	214	145	434	570	2124	Oligo	Oligo	AKV	Monthly to bi-monthly	Subbasin
Lake Brienz	N	BE	5.17	29.8	259	173	564	980	1127	Mono	Oligo	AWA	Monthly	
Upper Lake Lugano	N	TI	4.69	27.5	288	171	271	4490	565.6	Mero	Eu	CIPAIS	Monthly to bi-monthly	Shared with Italy
Lake Walen	N	SG GL	2.5	24.2	151	105	419	520	1061	Mono	Oligo	WVZ, AFU SG, UWE GL	4 times a year	
Lake Murten	N	FR VD	0.55	22.8	45	22	429	580	693	Mono	Eu	BENEFRI	Monthly	
Lake Lucerne: Urnersee	N	SZ UR	3.16	22	200	144	434	731	2124	Oligo	Oligo	AKV	Monthly to bi-monthly	Subbasin
Upper Lake Zurich	N	SZ SG	0.47	20.3	48	23	406	69	1564	Mono	Meso	WVZ, AWEL, AFU SG, AFU SZ, UWE GL	Monthly to bi-monthly	
Lower Lake Lugano	N	TI	1.14	20.3	95	55	271	511	565.6	Oligo	Eu	CIPAIS	Monthly to bi-monthly	Shared with Italy
Lake Sempach	N	LU	0.66	14.5	87	44	504	6170	77	Mono	Meso	UWE LU	Monthly	
Lake Hallwil	N	AG	0.285	10.3	48	28	449	1420	128	Mono	Meso/Eu	ABVU/AA	Monthly	
Lake Gruyère (de)	A	FR	0.22	9.6	75	21	677	75	954	Mono				Reservoir

Name	Type	Canton	Volume	Surface area	Maximum depth	Average depth	Altitude	Residence time	Catchment area	Mixing regime	Trophic state	Who is monitoring?	Frequency	Comment
			km^3	km^2	m	m	m	day	km^2					
Lake Joux (de)	N	VD	0.145	8.77	32	18	1004	300	211	Di	Meso	DGE VD	10 times a year	Used as reservoir
Greifensee	N	ZH	0.15	8.5	32	18	435	400	160	Mono	Eu	AWEL	Monthly	
Lake Sarnen	N	OW	0.239	7.5	51	31	469	290	268	Mono	Oligo			
Aegerisee	N	ZG	0.36	7.3	83	49	724	2500	4068	Mono	Oligo	AfU ZG	4 times a year	
Lake Baldegg	N	LU	0.174	5.2	66	33	463	1530	74	Mono	Eu	UWE LU	Monthly	
Lake Livigno (di)	A	GR	0.164	4.71	119		1805		295					Reservoir, shared with Italy
Lake Lucerne: Alpnachersee	N	NW OW	0.1	4.5	35	22	434	100	2124	Mono	Meso/Eu	AKV	Monthly to bi-monthly	Subbasin
Schiffenensee	A	FR	0.002	4.25	38		532		1400					Reservoir
Wägitalersee	A	SZ	0.15	4.18	65		900		43	Di				Reservoir
Lake Sils	N	GR	0.137	4.1	71	35	1797	800	45.8	Di	Oligo			
Pfäffikersee	N	ZH	0.059	3.3	36	19	537	760	40	Mono	Meso	AWEL	Monthly	
Klöntalersee	N	GL	0.056	3.3	45		848		83	Di				Used as reservoir, artificially increased
Lake Lauerz	N	SZ	0.234	3.1	13	7.6	447	123	123	Di	Meso/Eu	AfU SZ	3 times a year	
Lake Silvaplana	N	GR	0.14	2.7	77	48	1791	250	129	Di	Oligo			
Lake Lungern	N	OW	0.065	2	68	33	688	100-200		Mono				Reservoir
Lake Poschiavo (di)	N	GR	0.12	1.98	85		962		168	Di	Oligo/Meso			Reservoir
Lake Vogorno (di)	A	TI	0.1	1.68	204		470		233	Mono				Reservoir

Table A.1: List of some of the largest basins in Switzerland with several characteristics. Abbreviations regarding the mixing regimes are: Mero: meromictic; Oligo: oligomictic; Mono: monomictic; Di: dimictic. Abbreviations regarding the trophic regimes are: Oligo: Oligotrophic; Meso: Mesotrophic, Eu: Eutrophic. Abbreviations regarding the institution in charge of the monitoring are: ABVU AA: Amt Bau, Verkehr und Umwelt Aargau; AFU SG: Amt für Umwelt des Kantons St. Gallen; AfU SZ: Amt für Umweltschutz, Kanton Schwyz, AfU ZG: Amt für Umwelt des Kantons Zug; AKV: Aufsichtskommission Vierwaldstättersee (Kantone LU, SZ, UR, NW, OW); AWA: Amt für Wasser und Abfall des Kantons Bern; AWEL: Amt für Abfall, Wasser, Energie und Luft des Kantons Zürich; BENEFRI: Arbeitsgruppe BENEFRI der zuständigen Gewässerschutz-Fachstellen der Kantone Bern, Freiburg, Neuenburg und Waadt (die3seen.ch); CIPAIS: Commissione Internazionale per la Protezione delle Acque Italo-Svizzere; CIPEL: Commission internationale pour la protection des eaux du Léman; DGE: Direction générale de l'environnement, canton Vaud; IGKB: Internationale Gewässerschutzkommission für den Bodensee; UWE GL: Umwelt, Wald und Energie, Kanton Glarus; UWE LU: Umwelt und Energie, Kanton Luzern; WVZ: Wasserversorgung der Stadt Zürich.

10.2 DETAILED METHODOLOGY OF THE ANALYSIS

10.2.1 Introduction

Within this study, we **assessed the minimum spatial and temporal resolution** for the monitoring system to be efficient. To do so, we evaluated the influences of different temporal and vertical measurements resolution on the precision of several lake's characteristics. We **used a one dimensional hydrodynamic model** (Simstrat) previously calibrated and validated for Lake Zurich (Schmid and Köster 2016) to test different vertical and temporal resolution. The ideal monitoring case was set as 1 m vertical and 1 hour temporal resolutions.

The methods are presented in two sections: the temporal resolution, the vertical resolution.

10.2.2 Temporal Resolution

In order to parametrize the importance of different temporal resolutions (time between each measurement), three different resolutions were applied, and a comparison with the daily measurements was effectuated. The three different resolutions used were **weekly** measurements, **bi-monthly** measurements, and **monthly** measurements. In order to have a more realistic perspective, we selected randomly one day within the resolution scale. Indeed, measurements are never effectuated on the same day because of meteorological parameters (i.e. strong winds) or human resources (i.e. holidays, WE).

A Monte Carlo simulation using 10000 iterations was performed in order to produce a probabilistic perspective by selecting randomly one day within the range considered.

The studied parameters with different temporal resolution were the following:

- Duration of stratification, and its trend
- Duration of mixing, and its trend
- Surface and bottom temperature trends
- Heat content trends

The parameters were defined as follows.

- Duration of Stratification

The duration of summer stratification was defined as the longest uninterrupted period with daily temperature differences higher than 0.2 °C between the top (surface) and bottom layer, as already done in previous studies (Kobler et al. 2018).

- Mixing Duration

In analogy to the duration of stratification, the duration of the winter mixing was defined as the longest uninterrupted period with daily temperature differences smaller than 0.2 °C between the top (surface) and bottom layer. Please note that there is some transition period between the mixing and the stratified period, where the daily temperature difference fluctuates around 0.2 °C, hence the sum of the two periods can be different from 365 days.

- Heat Content

The total heat content *H* [J] of the lake was calculated according to the equation:

$$H = \int_{-D}^{0} \rho(z) \cdot C_P \cdot T(z) \cdot A(z) dz$$

The resulting heat contents for Lake Zurich were similar to those calculated in a previous study (Livingstone 2003).

- Trends

Trends were calculated using the Theil-Sen estimator, which is a robust non-parametric method for calculating trends. To calculate trends for each month of the year, first the mean monthly temperatures were calculated from the available data and then the long-term trend of the mean monthly temperatures were calculated. Schmid and Köster (2016) obtained very similar results for the surface temperature trends in the same lake.

10.2.3 Vertical resolution

In order to simulate different vertical resolutions, we used only the data at selected depths from of the complete 1-m resolution dataset from Lake Zurich. Density was calculated according to temperature using Lake Analyzer (Read et al. 2011).

The studied parameters with different vertical resolutions were the following:

- Thermocline position
- Epilimnion mean temperature
- Maximum stability

The parameters were defined as follows.

- Thermocline position

The thermocline was defined as the position of the highest density gradient. If this gradient was below 0.1 kg m^{-3} m^{-1}, the thermocline was neglected. If there were two peaks, usually representing one seasonal peak and one daily peak, only the peak located lower in the water column was taken into consideration as it represents the «Seasonal thermocline». Calculations and threshold values were performed by Lake Analyzer (Read et al. 2011). During winter when there is a weak stratification or no stratification at all, the thermocline was neglected. In order to determine the weak stratification period, we neglected the thermocline when the difference between the surface and the bottom water temperature was below the threshold of 1°C.

- Epilimnion mean temperature

The metalimnion was defined by the layer above and below the thermocline position where the density gradient was higher than 0.1 kg m^{-3} m^{-1}. The epilimnion layer is defined by the surface of the lake and by the top of the metalimnion, neglected in case of a weak stratification when the difference between surface and the bottom water temperature is below the threshold of 3 °C. The mean temperature in the epilimnion is calculated by a spline interpolation between measurements.

- Buoyancy frequency – Stability

The stability N^2 [s^{-2}] or buoyancy frequency, was calculated according to Wüest and Lorke (2003):

$$N^2 = -\left(\frac{g}{\rho}\right) \cdot \frac{\partial \rho}{\partial z}$$

We considered only the maximum stability N^2 of the water column, located at the thermocline position where the gradient of density is the highest.

10.3 TEMPORAL VARIABILITY – OTHER RESULTS

The influence of the temporal resolution on the accuracy when measuring stratification and mixing duration, as well as different heat content trends, is presented in Figure A.1.

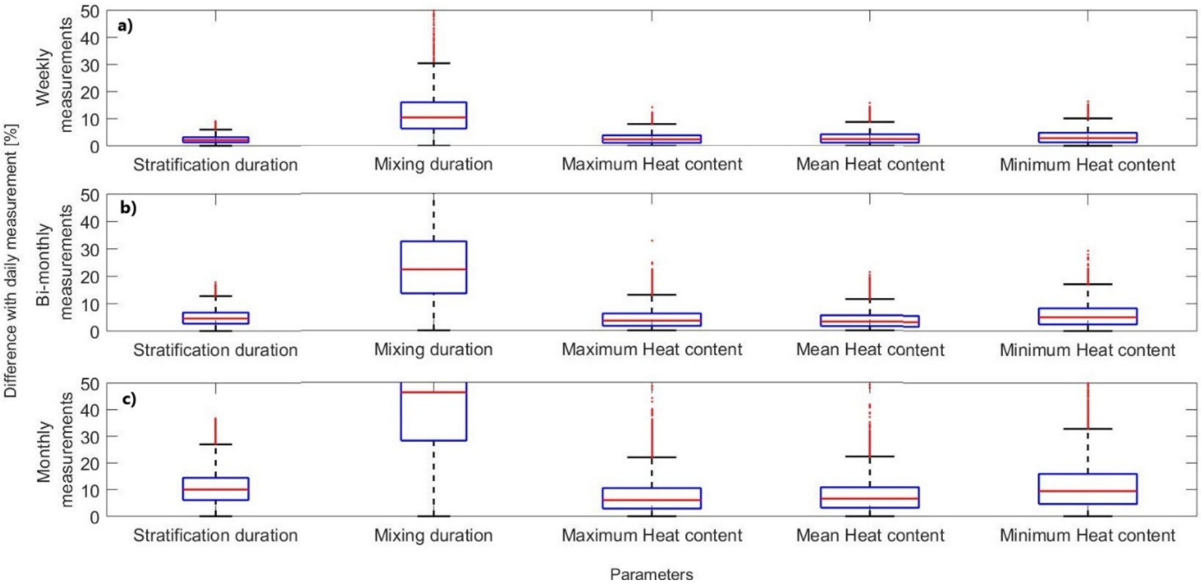


Figure A.1: Boxplots of the absolute difference compared to daily measurements of several parameters for three different temporal resolutions; a) Weekly measurements, b) bi-monthly measurements, and c) monthly measurements. The x-axis represents five different parameters: The duration of stratification, the duration of mixing, the maximum, the mean and the minimum heat content trends. In each boxplot obtained by a Monte Carlo analysis, the red line represents the median, the box lines represent the 25th and 75th quantiles, the error bars represent +/–2.7σ and the red points are the outliers.

As the duration of stratification is ~9 months, compared to a duration of mixing usually equal to 2-3 months, the percentage of difference is higher for the duration of mixing, where weekly measurements already lead to 25 % of the results with a difference higher than 16 %, and a median of 10.5 %.

For the duration of stratification monthly measurements result in median difference >10 % when compared to the real duration. This already implies that accurately predicting trends of the stratification duration is not possible with a monthly resolution, as presented in Figure 14 (Section 4.3).

Trends in heat content are affected to a lesser extent by the frequency of the measurements, but these differences are also already considerable enough to be avoided if possible.

10.4 SURVEY PRESENTATION

In order to precisely identify the needs and interests of data users, a survey was sent to 29 scientists and consultants working on lakes, of which 16 answered. This is a small number, but already representative enough to draw some conclusions. In this survey, we assessed different questions regarding the monitoring program. The survey was divided into four parts, with respective subjects assessed:

- User's identification: What is their work environment? Do they have actual critics regarding the temperature data?

- Monitoring characteristics: What are the vertical, lateral and temporal resolutions desired?
- Lakes characteristics: Which characteristics regarding lakes are important to consider?
- Further approaches and conclusions: Should we couple the new monitoring program with other monitoring activities? Any comments?

The entire survey is available on internet at this link: (https://docs.google.com/forms/d/e/1FAIpQLSdQq7dtksoAVb2OGik9ky9XnXyjSKj6jHSHcWuklwWyAEll7g/viewform?usp=sf_link).

The results of the survey are detailed here:

1. Characteristics of lake water temperature users

16 people answered the survey. Among them, 11 are working in research, 4 are consultant and 1 is working in a private company. The topics covered by the respondents are variable, but most of them are working on the evaluation of the effects of temperature and climate change on lakes (e.g., biogeochemical processes, algal blooms, carbon turnover, stability, stratification, species and fish habitats, ecology, phytoplankton dynamics…).

All respondents use lake temperature data for their work, 18.8 % every day, 37.5 % every week, 37.5 % every month, and 6.3 % on an annual basis. Regarding the accessibility of the data, 50 % have an easy access while 50 % think the access to the wanted data is limited. However, 68.8 % think the data are not sufficient for their activity, and 31.2 % think the data are sufficient.

2. Monitoring characteristics

87.5 % think that it is important to monitor temperature at different spatial (horizontal) locations in a lake. Regarding the locations, Figure A.2 represents the results of the survey. Other locations were specified in the comments. One suggestion was to monitor the temperature near a water abstraction (drinking water supply, thermal use, etc.), another suggestion was to take several profiles at different depths to determine heat budgets. Another comment states that the near shore temperature would be important to monitor to study internal waves and release of nutrients from the hypolimnion. One remark highlight differences usually occurring in lakes with several basins.

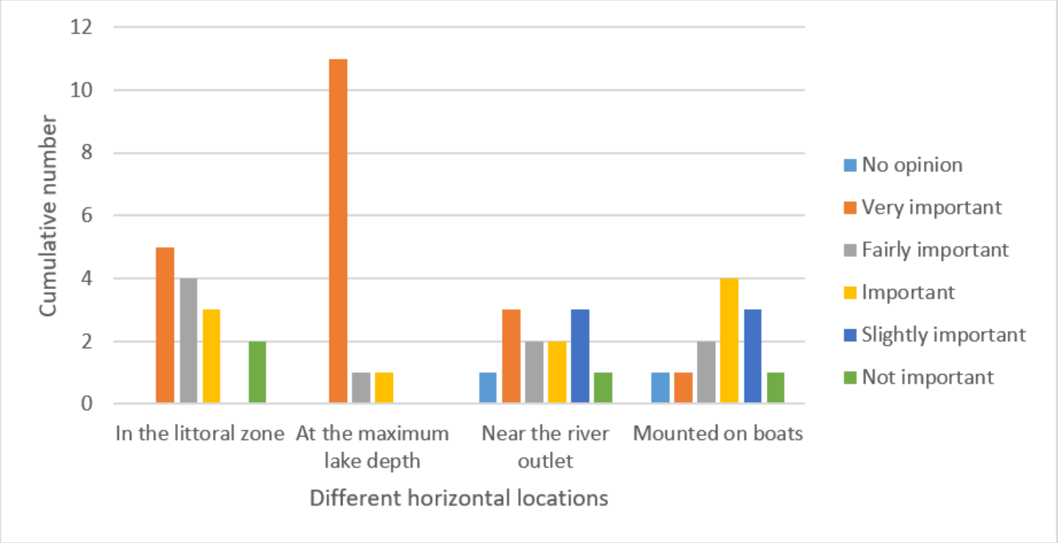


Figure A.2: Results of the survey concerning the importance of measuring temperature at different horizontal locations.

Regarding the depth at which the temperature should be monitored, results are presented in Figure A.3. One comment stated that the temperature should be monitored in the epilimnion.

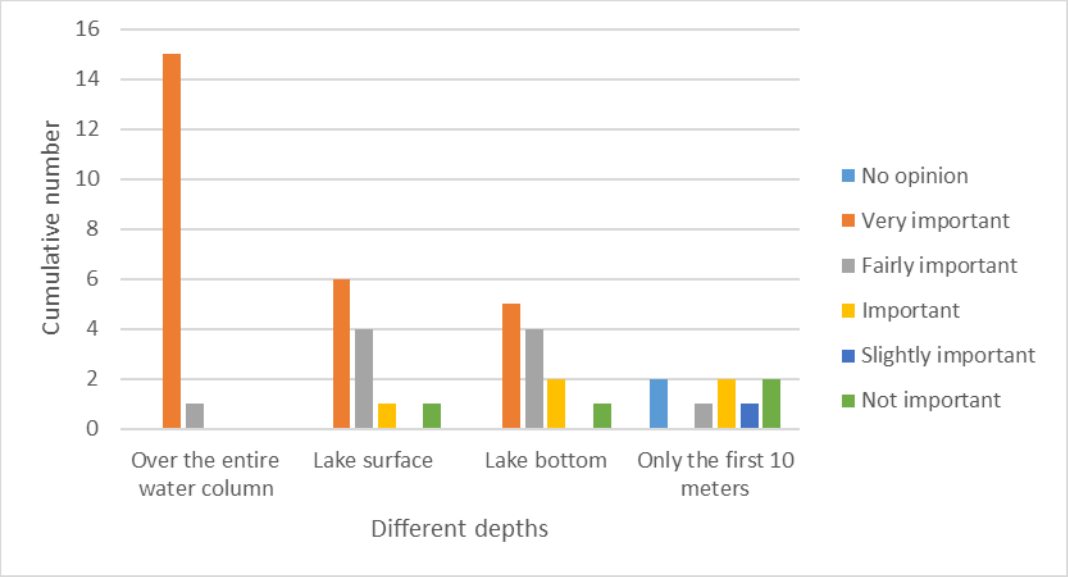


Figure A.3: Results of the survey concerning the importance of measuring temperature in different depth ranges.

When asked about an optimal and feasible vertical resolution for a lake monitoring system, the respondents answered with the following remarks: 0.1 m (1 respondent), 0.5 m (2), 0.5 to 1 m (1), 1 m (1), 1-2 m (1), 2 m (1), 1 m in the upper 10 m and 10 m for deeper layers (1), 1-2 m at the surface, 1 m at the typical thermocline depth, 2 m close to the bottom (1), at the surface, bottom and 5 to 7 other depths (1), and at every 0.1 °C change (1).

Figure A.4 represents the views of the respondents concerning the optimum and minimum temporal resolution.

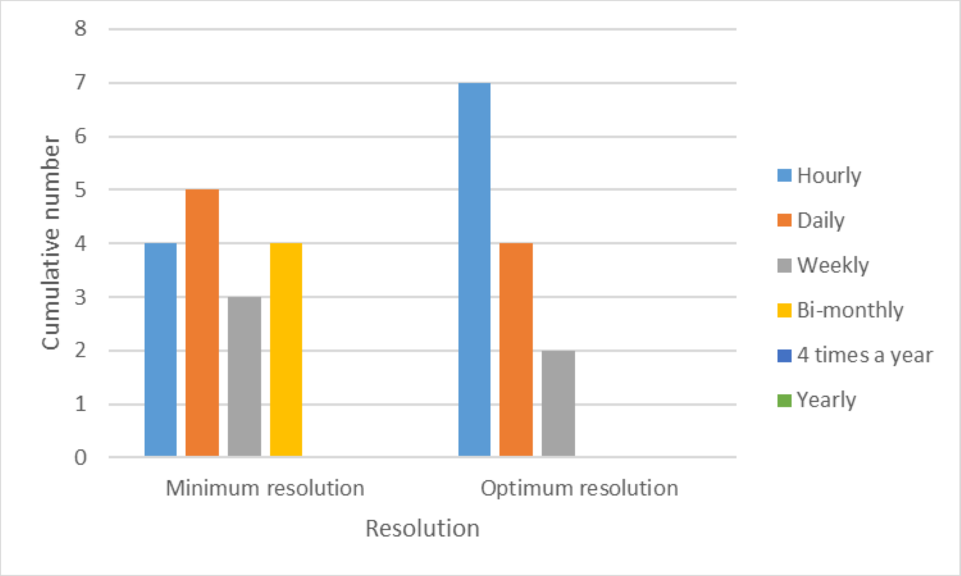


Figure A.4: Results of the survey concerning the minimum and optimum temporal resolutions of a lake monitoring system.

One comment highlighted the importance of having a higher resolution in times of rapid changes of temperature, while another comment stated that the maximum and minimum for each day would be good enough.

3. Lake characteristics

Figure A.5 represents the properties of lakes that need to be taken into consideration for the monitoring program according to the respondents of the survey. Lakes should differ in the properties where the votes are high. Comments for this question said that the monitoring should also take into consideration other impacts such as hydropeaking or water level regulations (for the anthropogenic impacts).

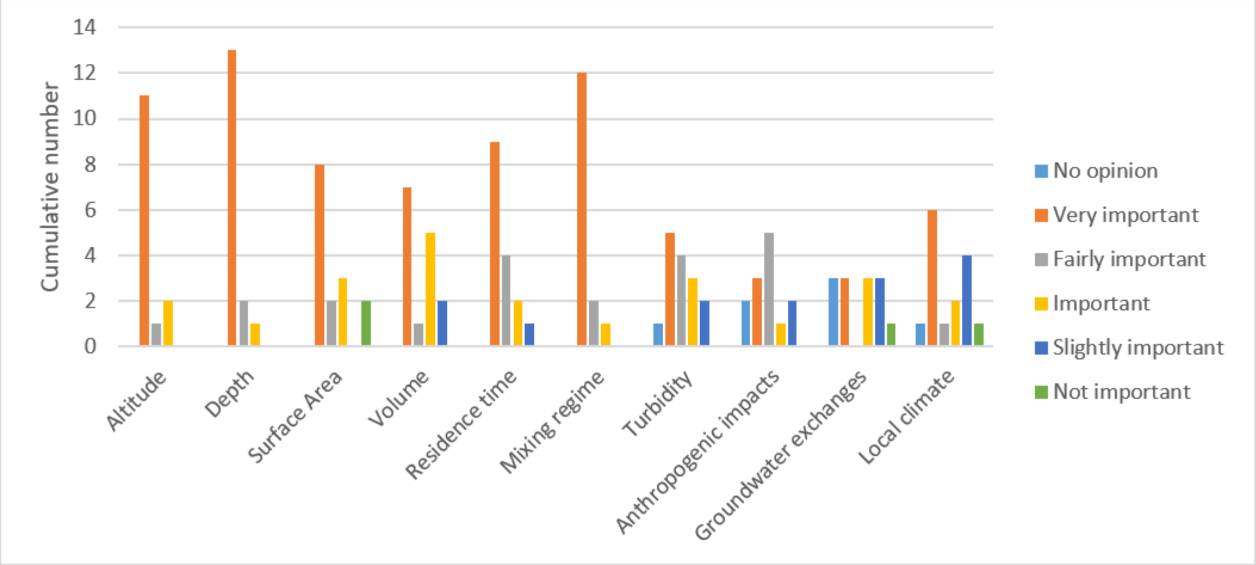


Figure A.5: Results of the survey concerning the importance of including lakes in a monitoring network that vary in specific characteristics.

81.3 % of the concerned people would be interested in monitoring small lakes. The reasons or comments for such a monitoring are the following:

- Most knowledge is lacking on small lakes
- These lakes are not modelled
- These lakes are very important to monitor carbon turnover and climate change.
- Impacts on greenhouse gas emissions
- To understand fish species assemblages
- Most susceptible to climate change and consequent effects on ecology
- Data from reference waters are usually missing for the aquatic ecological assessment of smaller waters

33.3 % of the concerned people would be interested in monitoring proglacial lakes.

4. Further approaches

Figure A.6 shows the importance assigned by the respondents to other monitoring activities that could complement the temperature monitoring. The following comments were made to this question:

- Measures of phytoplankton pigments, O_2, CO_2, etc, would be useful
- Meteorological data should include radiation, temperature (air and wet bulb), wind, humidity, pressure, precipitation, cloudiness
- Chlorophyll-a should be monitored
- Regarding the meteorological data, the wind is the most important

- Oxygen conditions.
- Water chemistry and micro pollution are important components, but my experience taught me that, as you cannot get them easily from sensors, very few information can be extracted from 1-4 times samplings during the year despite the heavy work load

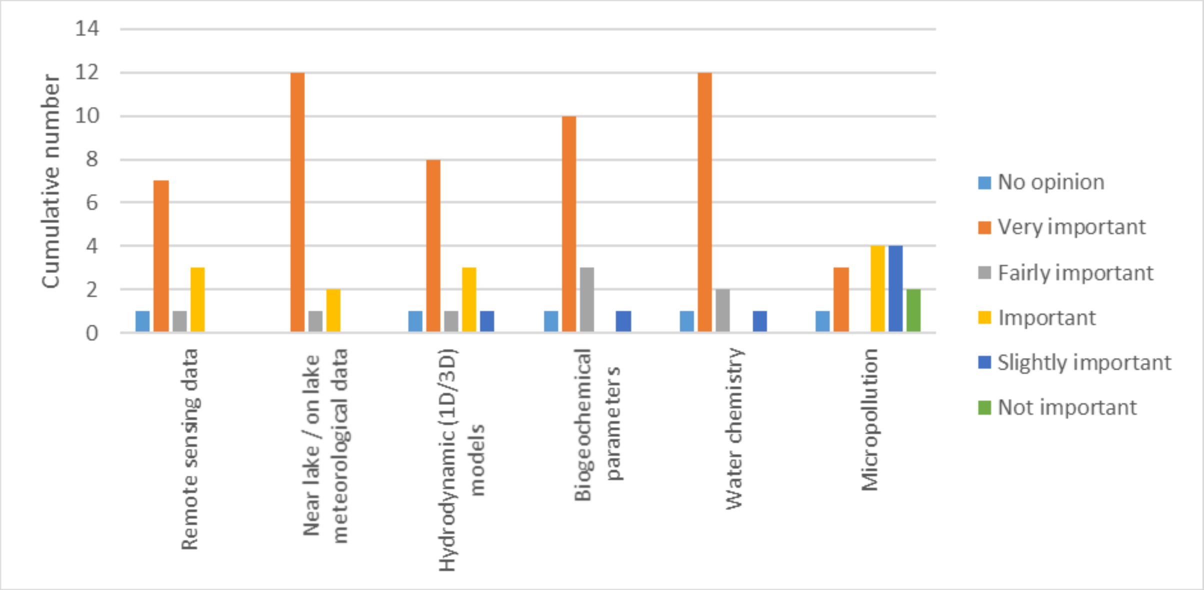


Figure A.6: Results of the survey concerning the importance of monitoring activities that could complement the temperature monitoring.

Further general suggestions made by the respondents were:

- It would be practical to build on existing monitoring programs, thanks to the availability of historical data series and logistic infrastructure and instruments (e.g. platforms, CTDs, etc).
- I would suggest a meeting with interesting parties to discuss key components and strategies.
- Formats must be homogenised.
- Better databases and integration of monitoring approach.
- Easy and public access to monitoring data, clear and graphic illustrations like in Meteolakes.ch.

Other questions regarding key scientific papers to investigate, or recommendations regarding international temperature monitoring program to investigate are not presented here but were studied to build this report.

10.5 MIXING REGIME DEPENDENCY TO ALTITUDE AND AVERAGE DEPTH

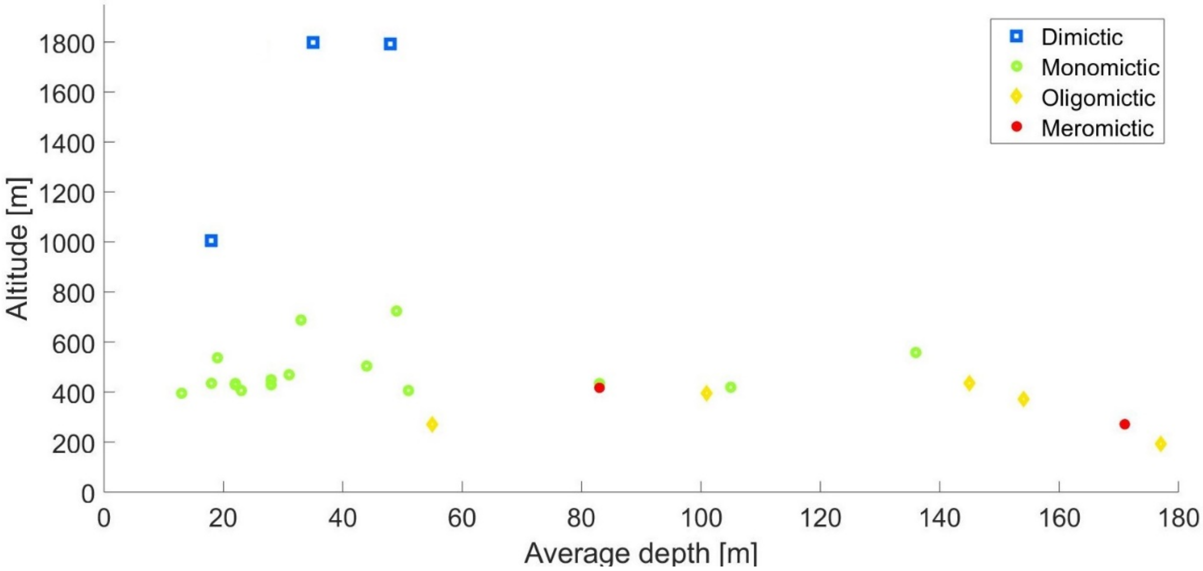


Figure A.7: Mixing regime of the 26 largest natural basins in Switzerland according to their altitude and their average depth. The mixing regimes are differentiated by the colours and shapes: blue squares indicate dimictic, green circles monomictic, yellow diamond oligomictic and red points meromictic lakes. Note that some lakes are divided in several basins (e.g, Lake Luzern).

Figure A.7 shows the strong dependence of mixing regime on altitude and depth. The higher and the smaller the lake, the more often and the stronger the mixing. Note that it is not always the case with, for instance, Lake St Moritz (not presented here) that is an oligomictic lake even though it is located at a high altitude (1768 m) and has a relatively small average depth (26 m). At this altitude, almost all lakes are dimictic, but in Lake St Moritz, a small river provides a saline inflow that creates a stable stratification (Schmid and Dorji 2008). Figure A.7 also indicates that high altitude lakes are generally small, as explained above.

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