

1 Original Research Article  
2 Climatic factors affecting water quality under  
3 natural conditions: a field survey of a local reservoir


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## ABSTRACT

The global water cycle is closely related to climate change, and fresh water is a precious resource. Therefore, the effects of climate change on fresh water quality are of major importance. Worldwide, shallow lakes and ponds are the most abundant reservoir types. However, there have been few studies about ponds despite their large number. It is commonly accepted that wind-driven currents and thermal stratification mainly affect water circulation and oxygen diffusion in lakes. The presented research aims to verify whether this accepted view would be observed in a pond ( $\sim 1$  m depth and  $\sim 5,600$  m<sup>2</sup> area) under natural conditions accompanying changes in temperature and wind. A field survey performed over 7 months in Japan has demonstrated that (i) the temperature variations in the air and the pond water were negatively correlated with the dissolved oxygen concentration; and (ii) the wind variation shows weak negative correlation with the dissolved oxygen level in the bottom layer. A simple concept of the link between temperature and dissolved oxygen is established through these findings – the oxygen solubility dependent on temperature is important rather than thermal stratification and wind in terms of discussing the climate change effects on pond water quality.

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*Keywords: Dissolved oxygen, Pond, Shallow lake, Temperature, Wind* 

## 1. INTRODUCTION

Global climate change is often thought of as something that will happen in the future, but it is an ongoing process [1]. Changes in Earth's climate, driven by increased greenhouse gases, are already having widespread effects on the environment such as droughts, wildfires, and

37 torrential downpours [2]. The global water cycle is closely related to climate change, land  
 38 use and the environment through complex interactions [3] — water is fundamental to all life  
 39 on Earth; for example, water makes up about 70% of the human body by weight, so a loss of  
 40 only 4% of water from the body leads to dehydration and a loss of 15% results in death [4 &  
 41 5].

42 Regarding the sources of water indispensable to life, the main ones include fresh surface  
 43 water, which accounts for just 1/10,000 of the total water available on the planet [6], and on  
 44 a global scale the amount of fresh surface water is almost constant over time, being  
 45 replenished by water precipitation previously evaporated from the ocean (~350,000 km<sup>3</sup>) and  
 46 land areas (~70,000 km<sup>3</sup>). Most precipitation falls back into the ocean, and only ~110,000  
 47 km<sup>3</sup> falls on the land; that means, fresh water is a scarce resource. About 4 billion people  
 48 currently experience water shortages for at least one month of the year [7], and these water  
 49 crises place third in a list of impact risks [8]. Modification in the distribution of groundwater  
 50 recharge and river flows over space and time are determined by changes in temperature,  
 51 evaporation and, mainly, precipitation [9]. Therefore, the effects of climate change on fresh  
 52 water quality seem to be an urgent issue that confronts not only human beings but also  
 53 many other species. This paper attempts to elucidate the interaction between climate  
 54 change and water quality on the basis of a field survey of a local reservoir, to assess  
 55 dissolved oxygen differences in ponds.

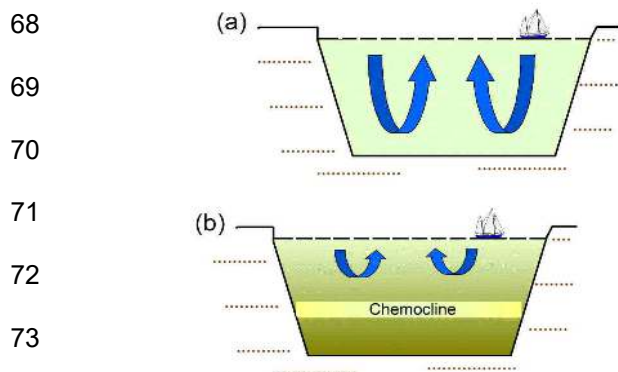
56 **2. BASIC INFORMATION** 

57 Multidisciplinary knowledge may be required to understand the relation between climate  
 58 change and water quality in reservoirs such as lakes and ponds. The overall aim of this  
 59 paper is to present a comprehensive case study on the relation of water quality with climate  
 60 change; therefore, basic information about key factors is briefly reviewed first, followed by a  
 61 description of the main discussion.

62 **2.1 Holomictic and meromictic**

63 A lake can be basically classified as holomictic or meromictic in terms of mixing [10].  
 64 Holomictic lakes follow a seasonal cycle of stratification and complete mixing (Fig. 1a), but  
 65 meromixis is a condition in which a lake does not mix completely [11] (Fig. 1b).  
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75 **Fig. 1. Conceptual pattern of water circulation in lakes (redrawn from [12 & 13]):** (a)  
 76 *holomictic lake — physical circulation (i.e. mixing) occurs between the surface and the deep waters;*

77 *and (b) meromictic lake — circulation is possible only within a layer, so turnovers from top to bottom do*  
 78 *not occur. A chemocline (i.e. transition zone) is commonly formed and separates the upper and lower*  
 79 *layers.*

80 In holomictic lakes, the water body circulates at least once a year due to homothermal  
 81 conditions, and mixing is complete or partial. The circulation homogenizes oxygen and  
 82 nutrient concentrations throughout the water mass [14].

83 In meromictic lakes, the lack of circulation between layers creates radically different  
 84 environments for organisms to live in: among the consequences of this stratification, or  
 85 stable layering, of lake waters is that the bottom layer receives little oxygen from the  
 86 atmosphere, hence becoming depleted of oxygen. While the surface layer may have 10 mg/l  
 87 or more dissolved oxygen in summer, the depths of a meromictic lake can have less than 1  
 88 mg/l [15].

89 Most lakes on Earth are holomictic, whereas meromictic lakes are rare [14]. However, in the  
 90 case of Lake Biwa (the largest lake in Japan, see also Fig. 2) having about 670 km<sup>2</sup> of  
 91 surface area and 41 m of mean depth, for the first time in recorded history, full circulation  
 92 was not observed in 2018, and this phenomenon continued in 2019 [12]. A warmer than  
 93 usual temperature continued at that time [12]. Hence it can be considered that the lake  
 94 turnover did not occur completely because the water density did not change due to the  
 95 insufficient function of temperature. As Lake Biwa is a main source of drinking water for 14  
 96 million people in the Kansai region of Japan [16], the quality degradation of the lake water  
 97 became a potential threat to the neighboring population, agricultural irrigation and regional  
 98 ecosystems [17, 18 & 19].

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100 **2.2. Shallow lakes and ponds**

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102 Worldwide, shallow lakes and ponds are the most abundant water reservoirs on land, and  
 103 these reservoirs supply lots of ecosystem services, goods and materials [20]. Many shallow  
 104 lakes and ponds have been created by humans after millennia of landscape modification,  
 105 such as stream and river impoundment. It is considered that the historical undercounting of  
 106 small lakes and/or ponds has led to a significant underestimation of the world's lake and  
 107 pond area [20].

108 As stated above, there are many shallow lakes and ponds throughout the world. They are  
 109 usually wind-exposed [11]. After thermal stratification develops during the daytime, full  
 110 circulation takes place at night due to wind-induced mixing and convection from surface  
 111 cooling [21]. Regarding the diurnal mixed layer in a shallow lake, the relative buoyancy ( $\epsilon \cdot g$ )  
 112 caused by solar radiation can be expressed as follows (cf. [21 & 22]):

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114  $\epsilon \cdot g = (\Delta\rho/\rho_0) \cdot g = \epsilon_0 \cdot g \cdot \exp(-z/H) \text{ — (I)}$  

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116 where  $\rho_0$  is the reference density of water,  $\Delta\rho$  is the density variation caused by solar  
 117 radiation,  $g$  is the gravitational acceleration,  $\epsilon_0$  is the value  $\epsilon$  in the water surface,  $z$  is the  
 118 water depth, and  $H$  is the center of buoyancy.

119 Assuming that the wind blows at the point where the relative buoyancy is formed, the  
 120 integrated value of buoyancy  $B$  within the interval  $z=0$  to  $z=h$  is denoted as follows:

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122  $B = \int \epsilon_0 \cdot g \cdot \exp(-z/H) dz = \epsilon_0 \cdot g \cdot H \cdot [1 - \exp(-h/H)] \text{ — (II)}$

123

124 The value  $H$  is  $h/2$  where the cline (e.g. a layer in which the water property varies) exists in  
 125  $z=h$ , and the increment of potential energy  $P$  (cf. turbulent kinetic energy) represented by the  
 126 value  $B$  is expressed by the following equation:

127

128  $P = B \cdot (h/2 - z_0) = \epsilon_0 \cdot g \cdot H \cdot h \cdot [\frac{1}{2} \{1 + \exp(-h/H)\}] - H/h \{1 - \exp(-h/H)\} \text{ — (III)}$

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130 **3. FIELD SURVEY**

131 As stated in section 2.2, it is commonly accepted that wind-driven currents and temperature  
 132 variations (e.g. thermal stratification) mainly affect water circulation and oxygen diffusion in  
 133 lakes. This research aims to verify whether this accepted view is actually observed under  
 134 natural conditions accompanying changes in temperature and wind in ponds. The research  
 135 was carried out in Japan from June to December of 2021.

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137 **3.1. Survey area**

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139 There are about 160 thousand artificial ponds (i.e. water reservoirs) in Japan, and about  
 140 70% of them were built before the 17th century (the Edo period) in order to supply water for  
 141 agricultural activities [23]. Japanese ponds are generally characterized by an area lower  
 142 than 7,000 m<sup>2</sup>, a depth below 1.0 m and a storage capacity below 7,000 m<sup>3</sup> [24]. In  
 143 comparison with lakes and rivers, most ponds are not located in public water areas, but their  
 144 management has to follow the general environmental quality standards [24]; therefore, there  
 145 have been few reports about the study of ponds despite their large number.

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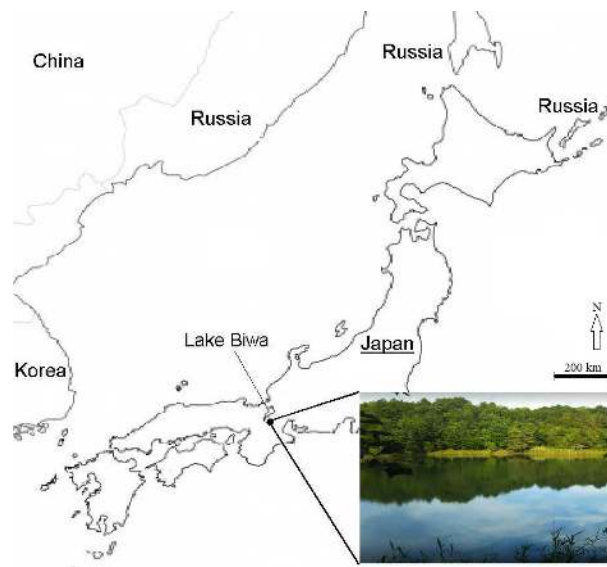
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166 **Fig. 2. Location of the study area (34°97'N and 135°93'E).** *The picture shows a view of*  
 167 *Nagao Pond.*

168 A typical pond was selected as the research target. The study focuses on Nagao Pond (Fig.  
 169 2), a kind of artificial water reservoir located on the north side (34°97'N and 135°93'E) of  
 170 Lake Biwa (section 2.1) in western Japan. The area encompasses about 5,600 m<sup>2</sup> and the  
 171 mean depth is about 1.5 m. The survey region belongs to a temperate zone with four distinct  
 172 seasons.

173 According to meteorological data in the research region [25 & 26], the snow period lasts for  
 174 1.5 months from January to mid-February, and the month with the most snow is February  
 175 with an average snowfall of 30 mm/month; the period of the summer season is about 3  
 176 months from mid-June to mid-September, and the maximum temperature is 26°C and the  
 177 average diurnal difference between the maximum and the minimum temperatures is 10°C;  
 178 the period of the winter season lasts for about 3.5 months from December to mid-March,

179 with average monthly maximum and minimum temperatures of 12°C and 0°C, respectively.  
180 Wind speed and the predominant wind direction vary throughout the year – winds often blow  
181 from the north at an average speed of 1.8 m/s during February-June and September-  
182 November, from the south at an average speed of 1.6 m/s during July-August, and from the  
183 west at an average speed of 2.2 m/s during December-January.

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### 185 ~~3.2. Materials and methods~~

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187 The spot information on wind speed and direction was gathered through a local climate  
188 database by JMA [25], and the procedures used in this survey are summarized below.

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#### 190 **3.2.1. Water sampling**

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192 Five points were chosen for water sampling, including the center section: the northeast  
193 section, the northwest section, the southeast section, the southwest section, and the center  
194 of Nagao Pond. Using a Heyroth sampler, 250 ml of water were collected from the surface  
195 layer and the bottom layer of each point, respectively. The sampling was carried out in the  
196 early afternoon once every 2 weeks, and two samples per point were collected.

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#### 198 **3.2.2. Measurements and analysis**

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200 The following parameters were measured in the field: (i) the water depth was measured  
201 using an ultrasonic echo sounder (Hondex PS7); (ii) the surface water temperature and the  
202 deep water temperature were measured using a digital multimeter (Hanna HI98129N); and  
203 (iii) the concentration of dissolved oxygen was determined using a digital oxygen meter with  
204 polarographic probe (Lutro PDO-520). In addition, a portion of each sample was promptly  
205 transported to a laboratory for the quantification of (iv) total phosphorus (TP) through  
206 molybdate colorimetry at 880 nm wavelength (cf. Japan Industrial Standard K0102 46.1.1);  
207 and (v  
208 ) ammonia nitrogen (NH<sub>4</sub>-N) by indophenol blue colorimetry at 630 nm wavelength (cf. Japan  
209 Industrial Standard K0102 42.6).

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#### 211 **3.2.3. Data processing**

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213 Using numerical analysis with R software, the correlation coefficient was applied to evaluate  
214 the relation between the temperature and the other parameters. The correlation coefficients  
215 interpreted in this paper are as follows:  $0 \leq |r| < 0.2$  indicates little or no association;  $0.2 \leq |r| < 0.4$   
216 indicates weak association;  $0.4 \leq |r| < 0.7$  indicates moderate association; and  $0.7 \leq |r| \leq 1.0$   
217 indicates strong association

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## 219 ~~4. RESULTS AND DISCUSSION~~

220 The data taken in this survey are summarized in Table 1. All data are shown as average  
221 values, which are considered to be representative. Variations in parentheses represent the  
222 minimum and maximum values measured.

223

### 224 **4.1. Water depth**

225

226 There is a clear difference between the least (0.4 m) and greatest values (1.0 m) of water  
227 depth, but the average depth varied slightly from 0.7 m to 0.8 m (Table 1). Viewing the  
228 detailed data for each survey point, the variations in water depth were similar ( $0.78 \pm 0.05$  m)  
229 at all sampling points except the northeast point; on the other hand, the water depth varied

230 from 0.4 m to 0.5 m at the northeast point; generally, the water depth at the northeast point  
 231 is about one half of that at the other points.  
 232 When considering all five sampling sites, the dissolved oxygen level does not vary  
 233 statistically from the surface layer to the bottom layer ( $p > 0.05$ ). Considering that dissolved  
 234 oxygen enters water through the air or as a plant byproduct (review in [27]), the following  
 235 hypothesis is proposed to interpret this specific phenomenon: oxygen originating in the air  
 236 can diffuse across the water's surface and be naturally mixed in a shallow pond, that is, the  
 237 diffused oxygen easily reaches equilibrium to some extent throughout the whole pond; and  
 238 even if a large portion of photosynthesis (e.g. phytoplankton) takes place underwater,  
 239 sunlight can penetrate shallow water and reach the bottom, meaning that the phytoplankton  
 240 is not likely to suppress the photosynthesis linked with oxygen supply.  
 241 Although Nagao Pond is man-made, it has an uneven bottom contour – i.e. deep and  
 242 shallow parts. It is reported that there are about 160 thousand artificial ponds and these  
 243 ponds are generally characterized by a depth of below 1.0 m (cf. section 3.1). Doubt remains  
 244 as to whether most of the other ponds have uneven bottom contours similar to Nagao Pond.

245 **Table 1. Average values of parameters measured at five sampling points in Nagao**  
 246 **Pond over the study period**

	Date	Water depth (m)	Wind (m/s)	Temperature (°C)			Dissolved oxygen (mg/l)		TP (mg/l)	NH <sub>4</sub> -N (mg/l)
				Air	Surface	Bottom	Surface	Bottom	Bottom	Bottom
June	2nd week	0.7 (0.5 - 0.9)	1.5 NW	24.2	29.4	28.5	4.8 (4.4 - 5.1)	4.8 (4.1 - 5.4)	NA	NA
	4th week	0.8 (0.5 - 1.0)	1.8 ESE	23.7	29.9	28.1	5.4 (4.8 - 5.9)	5.1 (4.9 - 5.1)	NA	NA
July	2nd week	NA	1.4 WNW	25.7	NA	NA	NA	NA	NA	NA
	4th week	0.8 (0.5 - 1.0)	1.6 NW	28.4	32.5	31.2	5.4 (5.1 - 5.8)	5.9 (5.1 - 6.2)	NA	NA
Aug.	2nd week	0.8 (0.4 - 0.9)	1.3 WNW	24.0	34.6	33.7	5.0 (3.7 - 6.0)	5.0 (4.3 - 5.4)	NA	NA
	4th week	0.7 (0.4 - 0.8)	1.4 ENE	28.0	30.3	29.9	5.8 (5.5 - 6.7)	5.9 (4.7 - 7.2)	NA	NA
Sept.	2nd week	0.7 (0.5 - 0.9)	1.0 NW	22.5	26.9	26.8	5.4 (5.5 - 6.1)	5.5 (5.2 - 6.3)	NA	NA
	4th week	0.7 (0.4 - 0.9)	1.8 ESE	23.8	25.1	24.8	5.8 (5.7 - 6.0)	5.9 (5.7 - 6.4)	NA	NA
Oct.	2nd week	0.7 (0.4 - 0.9)	1.5 NE	20.0	26.0	26.0	5.6 (5.2 - 6.1)	5.9 (5.2 - 6.5)	0.022	NA
	4th week	0.7 (0.4 - 1.0)	1.2 WNW	15.0	18.2	18.0	7.0 (6.7 - 7.3)	7.2 (6.8 - 7.5)	0.014	0.015
Nov.	2nd week	0.7 (0.4 - 0.9)	1.1 W	12.1	17.7	17.6	7.2 (6.8 - 7.7)	7.3 (6.9 - 7.8)	0.015	0.290
	4th week	0.7 (0.4 - 1.0)	1.4 E	9.6	16.7	16.3	7.6 (7.3 - 8.2)	7.6 (7.3 - 8.0)	0.016	0.180
Dec.	2nd week	0.7 (0.4 - 0.9)	1.3 W	7.7	13.4	13.4	8.0 (7.4 - 8.6)	8.1 (7.5 - 8.6)	0.009	0.425

TP - total phosphorus; NA- not available

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## 4.2. Eutrophication

250 Eutrophication is the nutrient enrichment of waters that stimulates an array of symptomatic  
 251 changes, including increased phytoplankton and rooted aquatic plant production, fisheries  
 252 and water quality deterioration, and other undesirable changes that interfere with water uses  
 253 [28]. Two primary nutrient cycles, phosphorus (P) and nitrogen (N), are generally focused on  
 254 anthropogenic perturbations and their cumulative effects [29]. Some threshold values for  
 255 eutrophication management range from 0.01 to 0.09 mg/l TP and 0.15 to 1.30 mg/l NH<sub>4</sub>-N  
 256 [29]. As seen in Table 1, the measured values are comparatively lower than the threshold

257 ones. On the other hand, Lake Kasumigaura, the largest shallow lake (about 4 m depth) in  
 258 Japan, continues to show typical signs of eutrophication [30]. This is due to the increased  
 259 nutrient loadings from urbanization, agricultural development and fishing culture [31].  
 260 Although the Environmental Quality Standard of TP is set to 0.03 mg/l, the TP value  
 261 increased from 0.04 mg/l to 0.10 mg/l in Lake Kasumigaura over the past 30 years;  
 262 meanwhile, the total nitrogen concentration also increased from 0.8 mg/l to 1.3 mg/l [32].  
 263 Continuous measurements of water quality parameters should be performed in Nagao Pond  
 264 to infer the actual/potential occurrence of eutrophication.

265

### 266 4.3. Climatic effect on dissolved oxygen

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268 As stated in sections 2.2 and 3, mainly wind-driven currents and temperature variations  
 269 affect water circulation in shallow lakes and ponds. It is therefore assessed whether such  
 270 climatic conditions are linked with the dissolved oxygen (DO) level near the bottom layer. As  
 271 seen in Table 2, the temperature variations in both air and water are negatively correlated  
 272 with the variation in bottom dissolved oxygen ( $r \approx -0.9$ ), and the temperature difference  
 273 between the surface layer and the bottom layer also shows moderate negative correlation ( $r$   
 274  $\approx -0.6$ ); by contrast, the wind variation shows weak negative correlation ( $r \approx -0.4$ ).

275 It can therefore be concluded that both the air temperature and the water surface  
 276 temperature dominantly affect the dissolved oxygen level in the bottom layer of a shallow  
 277 pond under natural conditions accompanying changes in temperature and wind.

278

279 **Table 2. Correlation coefficients ( $r$ ) of parameters measured in Nagao Pond ( $p < 0.05$ ).**

	Air temperature	Water surface temperature	Temperature difference between pond surface and bottom	Wind
- Dissolved oxygen in the pond bottom	-0.870	-0.922	-0.581	-0.369
- Correlation strength	Strong	Strong	Moderate	Weak

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281

282 As stated in section 2.2, pond stratification leads to the bottom layer receiving little oxygen  
 283 from the atmosphere, which may become depleted of oxygen. However, it is possible to  
 284 consider that stratification associated with temperature variation hardly occurs in a shallow  
 285 pond because there is no statistic evidence ( $p = 0.84$ ) showing a temperature difference  
 286 between the surface layer and the bottom layer. This may have resulted in a weak  
 287 correlation of the surface-bottom temperature difference with the dissolved oxygen level.  
 288 Other studies developed in a 1.8 m-deep pond also show no clear gradient of temperature to  
 289 a depth of 1.2 m [32]. Thus, it can be considered that a shallow pond is not thermally  
 290 stratified.

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## 291 ~~5. CONCLUDING REMARKS~~

292 The global water cycle is related closely to climate change. Fresh surface water accounts for  
 293 just 1/10,000 of the total water available on the planet (section 1), and shallow lakes and  
 294 ponds are worldwide the most abundant in lake types (section 2.2). It is accepted that wind-  
 295 driven currents and thermal stratification mainly affect oxygen diffusion and its dissolved  
 296 concentration in lakes (section 3). The present research aimed to verify whether this  
 297 accepted view would be really observed. Our field survey in a 1 m-deep pond has  
 298 demonstrated that (i) the temperature variations in the air and the pond water were  
 299 negatively correlated with the dissolved oxygen level in the bottom layer (section 4.3); (ii)  
 300 there was no statistic evidence showing a temperature difference between the surface layer  
 301 and the bottom layer (section 4.3.); (iii) there was no statistic evidence for differences in  
 302 dissolved oxygen concentration between the surface and bottom layers (section 4.1).

303 As to shallow reservoirs like ponds, a simple concept of the link between temperature and  
304 dissolved oxygen is established through these findings – the oxygen solubility in water  
305 decreases as the temperature increases [34].  
306 As stated above, fresh water is a precious resource worldwide, and shallow lakes and ponds  
307 are abundant worldwide. However, there have been few reports about ponds despite their  
308 large number (section 3.1). As the presented research was often restricted by the global  
309 pandemic, long-term observation is necessary to collect reliable data for underpinning the  
310 proper management of water reservoirs.



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