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Climatic Factors Affecting Water Quality under Natural Conditions: A Field Survey of a Local Reservoir

Ryunosuke Kikuchi [a,b*], Carla Sofia S. Ferreia [a,c] and Romeu Gerardo [d,e]

[a] *Centro de Recursos Naturais, Ambiente e Sociedade, ESAC / Instituto Politécnico de Coimbra, Coimbra, Portugal.*
[b] *Faculty of Science and Technology, Ryukoku University, Otsu, Japan.*
[c] *Department of Physical Geography and Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden.*
[d] *Universidade de Coimbra, CERIS, Coimbra, Portugal.*
[e] *Itecons Coimbra, Portugal.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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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 (Σ1 m depth and Σ5,600 m^2 area) under natural conditions accompanying changes in temperature and

**Corresponding author: E-mail: kikuchi@esac.pt;*

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.

Keywords: Climate change effects; pond; reservoir types; water quality.

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

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

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

1.1 Holomictic and Meromictic

A lake can be basically classified as holomictic or meromictic in terms of mixing [10]. Holomictic lakes follow a seasonal cycle of stratification and complete mixing (Fig. 1a), but meromixis is a condition in which a lake does not mix completely [11] (Fig. 1b).

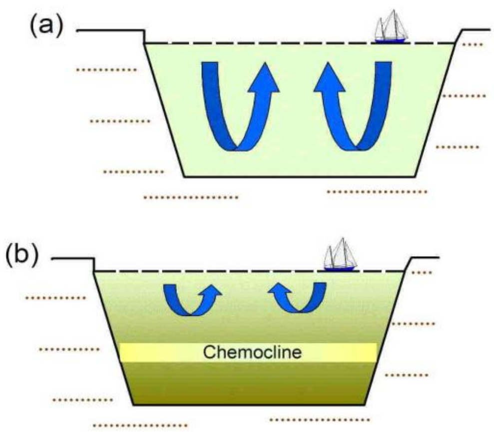

Fig. 1. Conceptual pattern of water circulation in lakes (redrawn from [12 & 13])

(a) Holomictic lake — physical circulation (i.e. mixing) occurs between the surface and the deep waters; and (b) Meromictic lake — circulation is possible only within a layer, so turnovers from top to bottom do not occur. A chemocline (i.e. transition zone) is commonly formed and separates the upper and lower layers

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

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

Most lakes on Earth are holomictic, whereas meromictic lakes are rare [14]. However, in the case of Lake Biwa (the largest lake in Japan, see also Fig. 2) having about 670 km² of surface area and 41 m of mean depth, for the first time in recorded history, full circulation was not observed in 2018, and this phenomenon continued in 2019 [12]. A warmer than usual temperature continued at that time [12]. Hence it can be considered that the lake turnover did not occur completely because the water density did not change due to the insufficient function of temperature. As Lake Biwa is a main source of drinking water for 14 million people in the Kansai region of Japan [16], the quality degradation of the lake water became a potential threat to the neighboring population, agricultural irrigation and regional ecosystems [17-19].

1.2 Shallow Lakes and Ponds

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

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

$$\varepsilon\cdot g = (\Delta\rho/\rho 0)\cdot g = \varepsilon 0\cdot g\cdot \exp(-ƶ/H) \qquad \text{(Eq. 1)}$$

Where $\rho 0$ is the reference density of water, $\Delta\rho$ is the density variation caused by solar radiation, g is the gravitational acceleration, $\varepsilon 0$ is the value ε in the water surface, ƶ is the water depth, and H is the center of buoyancy.

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

$$B = \int \varepsilon 0\cdot g\cdot \exp(-ƶ/H)dƶ = \varepsilon 0\cdot g\cdot H\cdot[1 - \exp(-h/H)] \qquad \text{(Eq. 2)}$$

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

$$P = B\cdot(h/2 - ƶ0) = \varepsilon 0\cdot g\cdot H\cdot h\cdot[½\cdot\{1 + \exp(-h/H)\}] - H/h\{1 - \exp(-h/H)\} \qquad \text{(Eq. 3)}$$

2. MATERIALS AND METHODS

As stated in section 1.2, it is commonly accepted that wind-driven currents and temperature variations (e.g. thermal stratification) mainly affect water circulation and oxygen diffusion in lakes. This research aims to verify whether this accepted view is actually observed under natural conditions accompanying changes in temperature and wind in ponds. The research was carried out in Japan from June to December of 2021.

2.1 Survey Area

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

A typical pond was selected as the research target. The study focuses on Nagao Pond (Fig. 2), a kind of artificial water reservoir located on the north side (34º97'N and 135º93'E) of Lake Biwa (section 1.1) in western Japan. The area encompasses about 5,600 m^2 and the mean depth is about 1.0 m. The survey region belongs to a temperate zone with four distinct seasons.

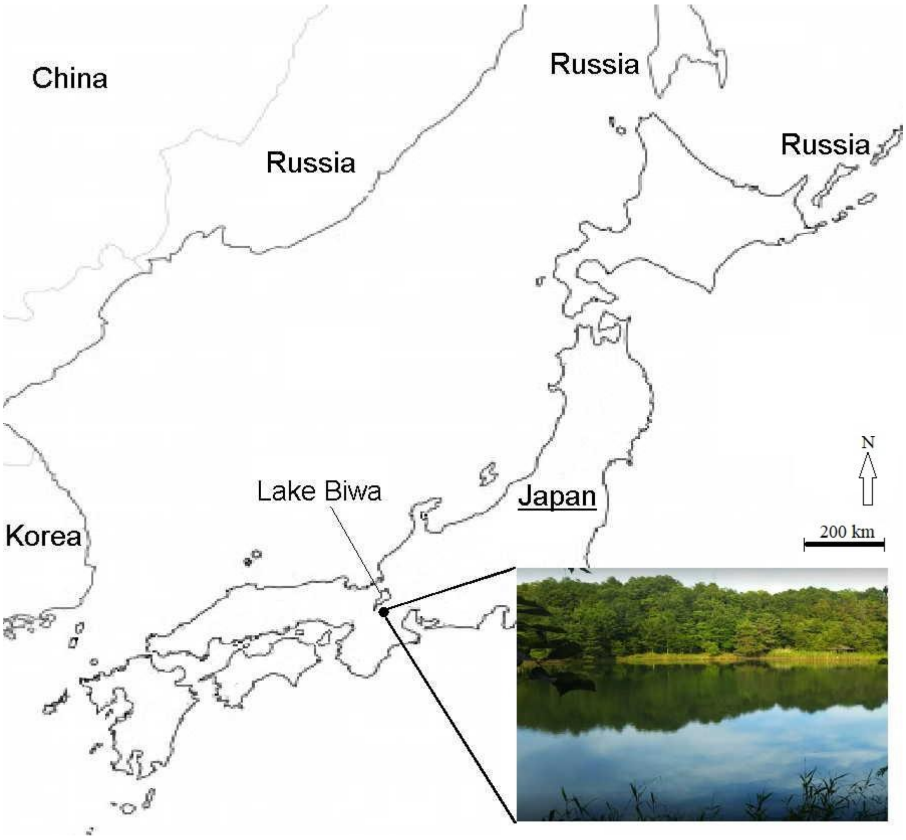

Fig. 2. Location of the study area (34º97'N and 135º93'E)
The picture shows a view of Nagao Pond

According to meteorological data in the research region [25,26], the snow period lasts for 1.5 months from January to mid-February, and the month with the most snow is February with an average snowfall of 30 mm/month; the period of the summer season is about 3 months from mid-June to mid-September, and the maximum temperature is 26ºC and the average diurnal difference between the maximum and the minimum temperatures is 10ºC; the period of the winter season lasts for about 3.5 months from December to mid-March, with average monthly maximum and minimum temperatures of 12ºC and 0ºC, respectively. Wind speed and the predominant wind direction vary throughout the year − winds often blow from the north at an average speed of 1.8 m/s during February-June and September-November, from the south at an average speed of 1.6 m/s during July-August, and from the west at an average speed of 2.2 m/s during December-January.

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

2.2 Water Sampling

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

2.3 Measurements and Analysis

The following parameters were measured in the field: (i) the water depth was measured using an ultrasonic echo sounder (Hondex PS7); (ii) the surface water temperature and the deep water temperature were measured using a digital multimeter (Hanna HI98129N); and (iii) the concentration of dissolved oxygen was determined using a digital oxygen meter with polarographic probe (Lutro PDO-520). In addition, a portion of each sample was promptly transported to a laboratory for the quantification of (iv) total phosphorus (TP) through molybdate colorimetry at 880 nm wavelength (cf. Japan Industrial Standard K0102 46.1.1); and (v) ammonia nitrogen (NH_4-N) by indophenol blue colorimetry at 630 nm wavelength (cf. Japan Industrial Standard K0102 42.6).

2.4 Data Processing

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

3. RESULTS AND DISCUSSION

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

3.1 Water Depth

There is a clear difference between the least (0.4 m) and greatest values (1.0 m) of water depth, but the average depth varied slightly from 0.7 m to 0.8 m (Table 1). Viewing the detailed data for each survey point, the variations in water depth were similar (0.78 ± 0.05 m) at all sampling points except the northeast point; on the other hand, the water depth varied from 0.4 m to 0.5 m at the northeast point; generally, the water depth at the northeast point is about one half of that at the other points.

When considering all five sampling sites, the dissolved oxygen level does not vary statistically from the surface layer to the bottom layer ($p > 0.05$). Considering that dissolved oxygen enters water through the air or as a plant byproduct (review in [27]), the following hypothesis is proposed to interpret this specific phenomenon: oxygen originating in the air can diffuse across the water's surface and be naturally mixed in a shallow pond, that is, the diffused oxygen easily reaches equilibrium to some extent throughout the whole pond; and even if a large portion of photosynthesis (e.g. phytoplankton) takes place underwater, sunlight can penetrate shallow water and reach the bottom, meaning that the phytoplankton is not likely to suppress the photosynthesis linked with oxygen supply.

Although Nagao Pond is man-made, it has an uneven bottom contour – i.e. deep and shallow parts. It is reported that there are about 160 thousand artificial ponds and these ponds are generally characterized by a depth of below 1.0 m (cf. section 2.1). Doubt remains as to whether most of the other ponds have uneven bottom contours similar to Nagao Pond.

3.2 Eutrophication

Eutrophication is the nutrient enrichment of waters that stimulates an array of symptomatic changes, including increased phytoplankton and rooted aquatic plant production, fisheries and water quality deterioration, and other undesirable changes that interfere with water uses [28]. Two primary nutrient cycles, phosphorus (P) and nitrogen (N), are generally focused on anthropogenic perturbations and their cumulative effects [29]. Some threshold values for eutrophication management range from 0.01 to 0.09 mg/l TP and 0.15 to 1.30 mg/l NH_4-N [29]. As seen in Table 1, the measured values are comparatively lower than the threshold ones. On the other hand, Lake Kasumigaura, the largest shallow lake (about 4 m depth) in Japan, continues to show typical signs of eutrophication [30]. This is due to the increased nutrient loadings from urbanization, agricultural development and fishing culture [31]. Although the Environmental Quality Standard of TP is set to 0.03 mg/l, the TP value increased from 0.04 mg/l to 0.10 mg/l in Lake Kasumigaura over the past 30 years; meanwhile, the total nitrogen concentration also increased from 0.8 mg/l to 1.3 mg/l [32]. Continuous measurements of water quality parameters should be performed in Nagao Pond to infer the actual/potential occurrence of eutrophication.

3.3 Climatic Effect on Dissolved Oxygen

As stated in sections 1.2 and 2, mainly wind-driven currents and temperature variations affect water circulation in shallow lakes and ponds. It is therefore assessed whether such climatic conditions are linked with the dissolved oxygen (DO) level near the bottom layer. As seen in Table 2, the temperature variations in both air and water are negatively correlated with the variation in bottom dissolved oxygen ($r \approx -0.9$), and the temperature difference between the surface layer and the bottom layer also shows moderate negative correlation ($r \approx -0.6$); by contrast, the wind variation shows weak negative correlation ($r \approx -0.4$).

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

	Date	Water depth (m)	Wind (m/s)	Temperature (℃)			Dissolved oxygen (mg/l)		TP (mg/l)	NH_4-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

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

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

As stated in section 1.2, pond stratification leads to the bottom layer receiving little oxygen from the atmosphere, which may become depleted of oxygen. However, it is possible to consider that stratification associated with temperature variation hardly occurs in a shallow pond because there is no statistic evidence ($p = 0.84$) showing a temperature difference between the surface layer and the bottom layer. This may have resulted in a weak correlation of the surface-bottom temperature difference with the dissolved oxygen level. Other studies developed in a 1.8 m-deep pond also show no clear gradient of temperature to a depth of 1.2 m [33]. Thus, it can be considered that a shallow pond is not thermally stratified.

4. CONCLUSIONS

The global water cycle is related closely to climate change. Fresh surface water accounts for just 1/10,000 of the total water available on the planet (section 1), and shallow lakes and ponds are worldwide the most abundant in lake types (section 1.2). It is accepted that wind-driven currents and thermal stratification mainly affect oxygen diffusion and its dissolved concentration in lakes (section 2). The present research aimed to verify whether this accepted view would be really observed. Our field survey in a 1 m-deep pond has demonstrated that (i) the temperature variations in the air and the pond water were negatively correlated with the dissolved oxygen level in the bottom layer (section 3.3); (ii) there was no statistic evidence showing a temperature difference between the surface layer and the bottom layer (section 3.3.); (iii) there was no statistic evidence for differences in dissolved oxygen concentration between the surface and bottom layers (section 3.1).

As to shallow reservoirs like ponds, a simple concept of the link between temperature and dissolved oxygen is established through these findings – the oxygen solubility in water decreases as the temperature increases [34].

As stated above, fresh water is a precious resource worldwide, and shallow lakes and ponds are abundant worldwide. However, there have been few reports about ponds despite their large number (section 2.1). As the presented research was often restricted by the global pandemic, long-term observation is necessary to collect reliable data for underpinning the proper management of water reservoirs.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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