# Effect of global warming on a deep lake and mitigation measures

By Michio Kumagai

Recent progression of global warming has resulted in the warming of surface waters and reduced vertical circulation in deep lakes and oceans. This has led to a decrease in primary production due to the lack of sufficient nutrient transport to the epilimnion and a significant impact on benthic ecosystems due to the shortage of oxygen supply to the hypolimnion. It has been pointed out that this fact not only has a significant impact on fish stocks, but also has the potential to cause the loss of endemic organisms in various parts of the planet. Since the 1990s, wave pumps have been used for energy utilization in the ocean, nutrient transport in fish farms, and removal of hypoxia. More recently they have also been used to control hurricanes. In the current preliminary experiments in Lake Biwa using hoses of 20 m or 40 m in length and 50 mm in diameter, water was transported upwards or downwards at the rate of about 1 $m^3$ every hour, showing the possibility to help enhance vertical circulation.

Lake Biwa, Japan

## Moving lake

Ancient Lake Biwa has a long history. It seems to have been formed about 4.2 million years ago near Iga Ueno in Mie Prefecture of Japan, which is almost 100 km south from its current position.

Around 3 million years ago, the direction of movement of the Philippine Sea tectonic plate suddenly changed from north to west, and it began to push the Japanese archipelago from the east. As a result, the Suzuka Mountains began to rise, and ancient Lake Biwa gradually began to move northwestward. This tectonic movement caused the undulation of the Earth's crust to rise and subside, which gradually caused subduction at the present position of Lake Biwa. Lake Biwa has been in its current location since between one million and 400,000 years ago. It now has an area of 670 $km^2$ with a 104 m maximum depth. Accordingly, Lake Biwa is one of the world's oldest freshwater lakes.

Most of the forms of aquatic life that live in the depths of Lake Biwa are endemic, which were transferred with the lake movement and became isolated millions of years ago. For example, *Bdellocephala annandalei Ijima and Kaburaki* are members of the planarian family that prefer cold water temperatures of 7°C-8°C and are survivors of the last Ice Age. They live at a depth of >70 m in Lake Biwa, so are rarely seen by the general public. In addition, *Gymnogobius isaza, Jesogammarus annandalei, Silurus biwaensis* and *Oncorhynchus masou rhodurus* living in deep layer are also endemic to this lake.

The effects of global warming are slowly impacting these cold-water organisms[1]. In a closed lake, unfortunately, they have nowhere to escape. Since 1985, we have been carefully watching these lake bottom organisms. We found that the full annual circulation of Lake Biwa stopped from 2018 to 2020 (Figura 1). This annual circulation completely replaces the old, low oxygen water near the bottom of the lake with fresh water containing high oxygen concentrations (>80 %) in the winter.

In 1993 we built a new research vessel (Hakken), which is a catamaran with a wide deck and a powerful crane. Using this vessel from August to September 1993, we carried out an international observation program called BITEX'93 (Biwako Transport Experiment), which was the world largest field experiment in a lake involving more than 165 scientists and students from seven different countries. After one month operation, we were able to identify the ecological and biogeochemical reactions created by two typhoons that occurred during the experiment period in September 1993 (TY9313 and TY9314). In 2000 we built an autonomous underwater vehicle AUV (Autonomous Underwater Vehicle) Tantan. As a result, the investigation of the bottom ecosystem of Lake Biwa has made great progress[2].

AUV Tantan took a photograph near the deepest part of the lake (Figure 2). In the fuzzy turbidity that bursts from the bottom, a family of endemic *B. annandalei* and couples of endemic *J. annandalei* are relaxing together. It is like a mud hot spring!

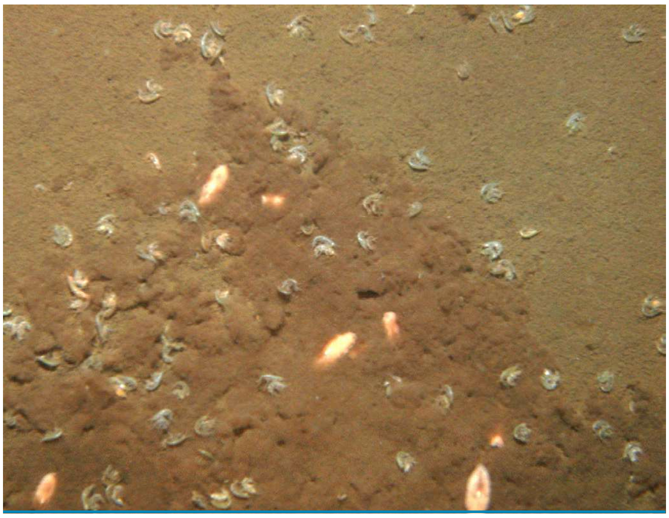

**Figure 2** | Family of *Bdellocephala annandalei* and couples of *Jesogammarus annandalei* lounging on the turbid bottom of Lake Biwa (photographed by AUV Tantan on 25 August 2006).

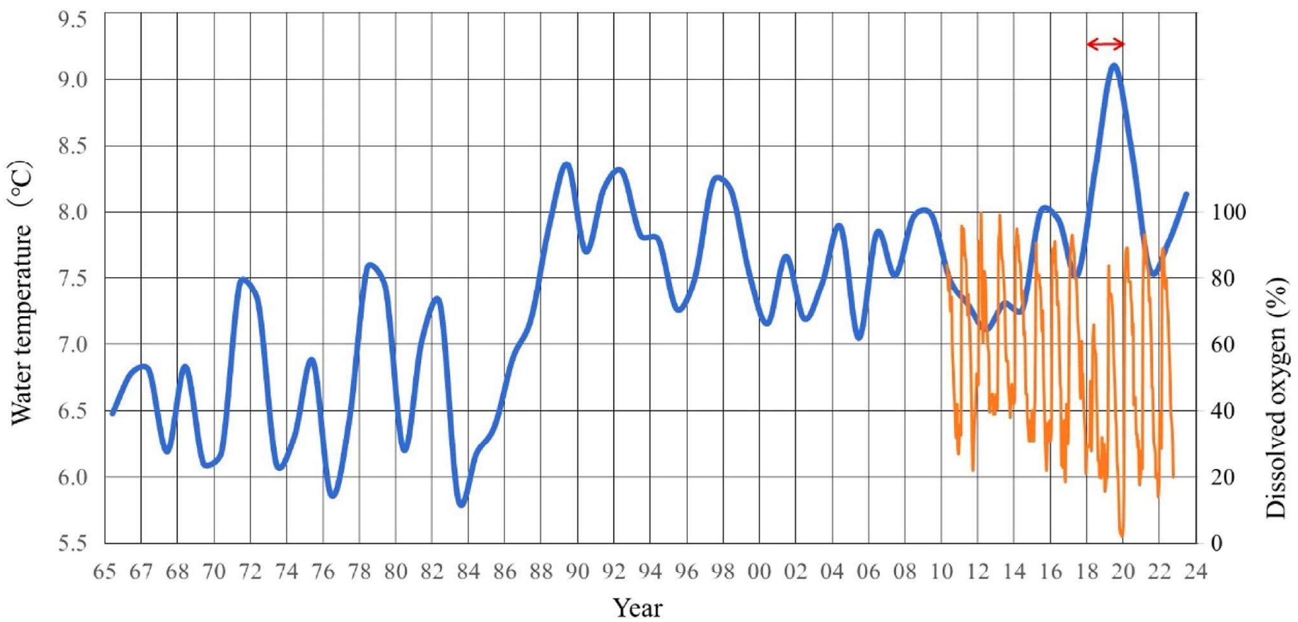


**Figure 1** | Annual average water temperature (blue line) at 93 m depth point of Lake Biwa (1965-2023) and dissolved oxygen (orange line) measured by LBERI (2011-2023). The red arrow indicates the period with no winter overturn.

We are not sure why they were gathering in this place. However, it looks like a very peaceful scene. We are sure there is something very good about this place for them, and we think that this sediment ebullition is one of the reasons why the deepest place of Lake Biwa has not been buried with sediments during the last 400,000 years after it was formed here.

From 22 to 28 July 2021, the year after the full circulation stopped, three AUVs (AUV Hoverin, AUV Hoverin 2, and AUV YOUZAN) were used to investigate if *B. annandalei* still lived at the bottom of the lake. Their numbers had plummeted, but they were confirmed to be still alive. At the same time, we noticed that the turbidity near the bottom of the lake was increasing significantly. It was no longer possible to take clear photographs of the beautiful world on the lakebed as seen in 2006. This was the moment when we had a feeling that something was wrong.

Above the bottom of Lake Biwa, a benthic boundary layer is formed during the stratification period from May to October. In this layer, the energy that enters the lake from the wind generates waves and changes its shape to turbulence, creating a very dynamic and active regime. Organic matter on the bottom is decomposed by bacteria, and oxygen dissolved in water is consumed[3]. As a result, the dissolved oxygen concentration decreases, and heavy metals and other toxic substances dissolve out from the mud at the bottom of the lake. Such heavy metals that come out of the sediments recombine with dissolved oxygen to form a suspended material that floats in the water. This is one of the main causes of turbidity as well as sediment ebullitions.

## Mitigation measures

How can we find a reasonable and effective means to recover full circulation in lakes and oceans where it has ceased? We have tried several methods and are looking for more inexpensive, easy to handle and safe technology, because most people do not like to change nature with high technology tools or chemically toxic methods.

Finally, we came up with the idea of using wave pumps, which take advantage of the huge amount of energy transferred by wind to the lake.

In a small-scale experiment with a wave pump off the coast of Hawaii in the 1970s, a pipe with a diameter of 35 mm was used to pump water from a depth of 90 m. It was proposed to use this wave pump energy to perform water electrolysis and keep energy storage in the form of hydrogen gas[4]. In addition, a recent trend in large-scale proposals is to use wave pumps as a countermeasure against global warming. For example, there are methods such as pumping nutrient-rich deep water to surface phytoplankton that absorb carbon dioxide from the atmosphere at the water surface, and ideas to suppress the development of hurricanes by creating water bodies with cooler surface temperatures[5].

In order to confirm the effectiveness of wave pumps, we conducted two field experiments in Lake Biwa from 19 to 27 June 2022 and from 17 to 24 February 2024. In 2022, we used an upwelling pump with a 20 m long flexible hose on the suction side and a downwelling pump with a 1-m long rigid tube with no flexible hose on the suction side. In the 2024 experiment, only a downwelling pump with a hose length of 40 m on the discharge side was used. In both cases, each wave pump hose was 50 mm in inner diameter and was fitted with a pulse-type flow meter (YF-DN50) and a digital data logger (LR5061) to measure the amount of water flux. One pressure-resistant buoy (diameter 386 mm, buoyancy 29.9 kg) was used, which could be freely raised and lowered by being connected with a rope to another bottom anchored buoy that served as fulcrum. The most important thing here was the installation of an original valve for each case of upwelling or downwelling, which subtly regulated the buoyancy. We used a little heavier valve for upwelling case and a little lighter one for downwelling case to keep water flow one way, respectively.

In a wave pump, the pump is suspended to a surface buoy so it can be thought of simply as an up-and-down motion device. A wave pump transports water because wind waves provide angular accelerated motion. The faster the wave vibrates, the greater the angular acceleration, and the more flow is caused by the wave pump.

In order to evaluate the efficiency of a wave pump, it is necessary to determine the characteristics (wave height and frequency) of the wind waves generated at the place where the pump is to be installed. Since the wind frequently changes its wind direction and speed, the waves also change from time to time. Therefore, statistical evaluation of waves is necessary. In general, when the wind speed, wind direction, and fetch (distance from the windward shore) are known, the significant wave heights and frequencies can be estimated.

As a result of simultaneous measurements of the upwelling and downwelling flow, it was possible to transport water with almost the same trend (Figure 3). It was found that wave pumps can transfer water quite efficiently. The upwelling flow was about 20% lower than the downwelling flow at high wind. This is presumed to be due to the frictional resistance caused by the fact that a 20 m long hose was attached to the upwelling wave

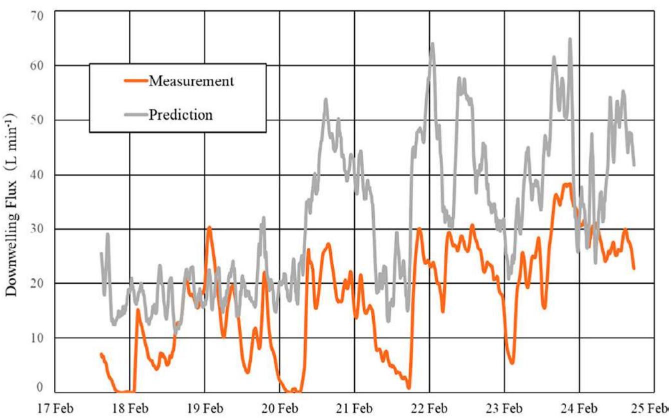


**Figure 3** | Wave pump experiment outputs in 2024. The upwelling pump had a 20 m suction hose and the downflow pump had no suction hose. The different head losses in the two cases may cause a slightly greater downward flow. The predicted values show the flow rate estimated from the significant waves calculated using the weather data of Imazu Station. The numbers are all 1-hour moving averages to round out the forecast error.

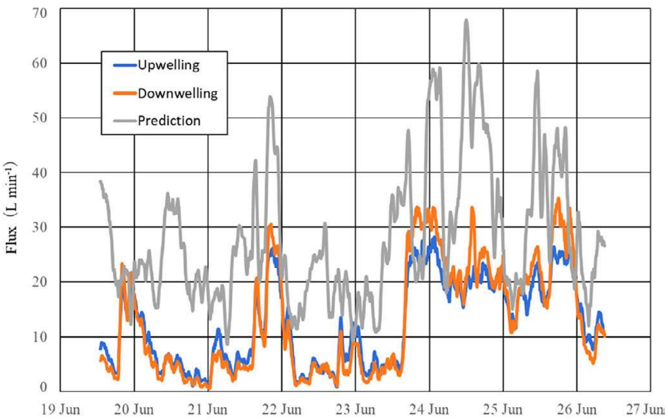


**Figure 4** | Wave pump experiment outputs in 2024. The downwelling pump is equipped with a 40 m hose. The predicted value shows the flow rate estimated from the significant waves calculated using the weather data at Imazu Station. The numbers are all 1-hour moving averages to round out the forecast error.

pump, and the inertial force when the wave pump is pulled upward. Using weather data from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency measured at the Imazu Station every 10 minutes, we calculated the significant wave heights at the site and calculated the predicted flow rate from the up-and-down motion of the pump. Measurements show that the water flux in the hose of the wave pump corresponds closely to the development of significant waves.

From 23 to 26 June, when the average 10-minute wind speed was 3 m sec$^{-1}$ or more, it was clear that the upwelling and downwelling flow rates were more than 15 L min$^{-1}$. In particular, the accumulated flow rate of the water that rose in the 50 hours from 23 to 26 June was more than 70 m$^3$. This means that 1.4 m$^3$ of water was transported every hour.

The results of the second experiment from 17 to 24 February 2024 also showed that the predicted flow rate estimated from the significant waves was correlated with the flow rate measured by the wave pump (Figure 4). Thus, the high correlation between the predicted values obtained from the wind data measured at Imazu and the actual values measured by the wave pump installed at the site ($R^2$ = 0.5467, n=1023, p<0.01) was a surprising result.

Also, it was found that the cumulative flow rate of water transported downward for 72 hours from 17 to 24 February was 109 m$^3$, or about 1.5 m$^3$ transported downward on the average every hour. This is almost the same amount as the upwelling transport volume of the first experiment, which confirms the stability and reliability of the wave pump.

Using these results, we determined the efficiency of the wave pump. In order to exclude errors due to time lag and variation in the measurement and prediction data in the two Lake Biwa experiments, the accumulated efficiency was estimated as the ratio of the measured flow volume obtained from wave pump experiments over the predicted flow volume based on the significant wave heights calculated from the wind speed, direction and fetch. A stable efficiency can be obtained in 20 to 40 hours after wave pump installation. In the first experiment in 2022, the efficiency of both the up flow and downflow was about 45%. In the second experiment in 2024, the accumulated efficiency of the downward flow exceeded 53% despite the installation of a 40 m long hose. Although this is still a preliminary assessment using easily obtained materials at low cost, we can conclude that wave pumps have a very high energy conversion efficiency. In order to obtain higher confidence in the efficiency estimates, more precise field data of wind waves and more well-designed devices are required.

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Michio Kumagai is a professor in the Research Center for Lake BIWA & Environmental Innovation, Ritsumeikan University, Japan. He was one of the overall coordinators of BITEX in 1993, gave the SIL Baldi Lecture in 2007, and was the President of the Japanese Society of Limnology from 2012 to 2015. He was the Co-Chair of the ASLO-Japan Aquatic Sciences Meeting in 2012 and is the Vice President of the Authorized NPO Biwako Trust from 2023. He was awarded the Commendation for Science and Technology by the Japanese Minister of Education, Culture, Sports, Science and Technology in 2024. His background is geophysics and limnology, and now works mainly on global warming and its mitigation in Lake Biwa with his students as part of his quest to save the world for future generations.