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Effects of artificial hypolimnetic oxygenation in a shallow lake. Part 1: Phenomenological description and management

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ABSTRACT

Artificial oxygenation is a common management technique for lake restoration, but the use of hypolimnetic aeration in shallow basins can have dramatic effects on the dynamics of thermal stratification. This study presents the results of extensive field measurements performed in Lake Serraia (Trentino, Italy) after the installation of a Side Stream Pumping System, whereby oxygen-rich water is injected through 24 jets, uniformly distributed along an octagonal-shaped pipe at approximately 1 m above the sediment floor (10 m in depth). The lake is characterised by an average depth of 7 m, a volume of 3.1×10^6 m^3 and a residence time of about one year. Prior to the installation of the pumping system, the undisturbed hypolimnion thickness during summer stratification was relatively small. After the start of oxygen injection (up to 0.5 m^3/s of oxygen-saturated water), an increase of in-lake temperature over the entire water column was noted with a maximum hypolimnetic temperature increase of up to 9 °C. The analysis of the flow field data and the results of numerical simulations (presented in the companion paper), indicate that the jets were solely responsible for the observed increase in temperature. Moreover, this study shows that modelling efforts are useful to provide guidelines for optimising contrasting needs (e.g., increase in oxygen supply versus jet discharge rate).

1. Introduction

Artificial oxygenation techniques aim to supply the additional oxygen needed for accelerated oxidation rates of settled organic matter (OM) in response to increased algal blooms associated with eutrophication events. These systems represent a commonly used practice in lake restoration (e.g., Beutel and Horne, 1999; Singleton and Little, 2006): their goal is to satisfy the sediment oxygen demand (SOD) and increase the redox potential at the water–sediment interface, limiting the seasonal release of nutrients from the bottom sediments into the water column. Eventually, the prolonged (typically for several years) oxidation of the OM in the superficial layer of lake's sediments can reduce the SOD and improve the trophic state if accompanied by a reduction of the external nutrients load. However, it has been noted that artificial oxygenation has not always proved completely successful, at least in the medium term (e.g., Gächter and Wehrli, 1998; Liboriussen et al., 2009), and the results depend on many factors related to both the design and physicochemical characteristics of the lake.

Small, shallow lakes characterised by relatively long water residence times are particularly susceptible to anthropogenic influences. This is the case for the peri-alpine Lake Serraia (Trentino, northern Italy, Fig. 1), where the annual characterisation of the trophic state performed by the local environmental protection agency (APPA) noted an anthropogenic-induced eutrophication starting in the late 90s. Lake recovery efforts resulted in plans for the reduction of external nutrient loads and led to the construction of a Side Stream Pumping System (according to the classification proposed by Singleton and Little, 2006) to provide an additional hypolimnetic oxygen supply.

In this study, we analyse the alteration of thermal stratification induced by the utilization of the artificial oxygenation plant at Lake Serraia. The system is composed by water jets distributed along an octagonal ring at approximately 1 m above the sediment floor. Due to the shallow nature of the lake and the presence of a thick metalimnion that, under natural conditions, previously spanned the depth of the sediment floor, deep aeration induced mixing within

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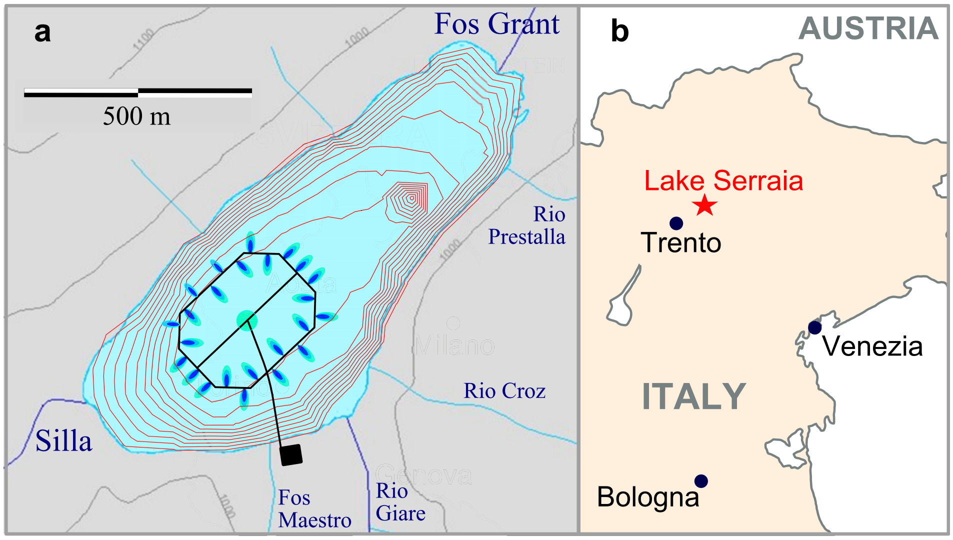

Fig. 1. (a) Bathymetric map of Lake Serraia and simplified scheme of the oxygenation ring. (b) Location of the study site within Italy.

the water column and resulted in an overall increase in lake temperature. The positive effects of the artificial oxygen supply could be counterbalanced by this warming effect because the increased temperature is likely to provide favourable conditions for increased algal lake productivity (primary production). Additionally, warming is associated with enhanced rates of OM decomposition, increased water circulation, sediment remobilisation and increased turbidity. Empirical evidence suggests that the oxygenation systems can increase the SOD, mainly due to the stronger mixing effect (Gantzer et al., 2009; Bryant et al., 2011). In the case of Lake Serraia, the two factors are strongly interrelated: the mixing induced by the system can immediately influence the SOD, but indirectly modifies the thermal profile causing an alteration of the lake thermal structure. Natural factors like seiching, which may also produce substantial changes in SOD (Bryant et al., 2010), do not produce comparable effects in this case.

Destratification is sometimes desired in order to improve the dissolved oxygen (DO) content in the hypolimnion by increased mixing with surface waters. This was not the case in Lake Serraia, where the attempt was to keep the natural stratification in order to preserve the habitat for the fauna living in the cold waters at the bottom of the lake. Another reason for the design of a system that should not alter the summer stratification was to avoid the possible production of evil-smelling gases by an incomplete oxidation of organic matter, which could have strong, negative impacts on the recreational use of the lake.

In such a condition, optimal management of the oxygenation system has to face two contrasting requirements, which need to be properly balanced. First, to provide an adequate oxygen supply, which is possible only through large water discharge volumes from the jets. Second, to limit the rate of deep water mixing, which is responsible for the alteration of thermal stratification. The theoretically possible solution to increase the concentration of dissolved oxygen in the returned water of this side-stream supersaturation system by increasing the operating pressure was not viable because of operational problems in the oxygenation and distribution systems. Therefore, the only possible solution consists of a set of suitable guidelines for the modulation of the jet discharge in order to balance the requested oxygen supply and the thermal conditions of the lake. To this end, a numerical model (presented in the companion paper, see Toffolon and Serafini, 2013) has been developed as a tool to derive suitable management practices.

In this paper we present the case study based on the field data survey (Section 2) and discuss the main factors responsible for the disruption of thermal stratification, the overall increase in temperature and the alterations in water quality (Section 3), also on the basis of the results of numerical modelling. Finally, we examine the present state to assess the outcomes of lake recovery.

2. Materials and methods

2.1. Study site

Located in northern Italy (Trentino region, see Fig. 1) at 974 m above sea level, Lake Serraia is a small, shallow, peri-alpine, dimictic lake. With an average depth of 7 m (maximum depth of 18 m) and a surface area of approximately 0.45×10^6 m^2, the lake has a total volume of approximately 3.1×10^6 m^3. With a general NE–SW orientation, the lake is characterised by a maximum length of 1 km along the main axis and an average width of approximately 450 m. The drainage basin of the lake is 11.6 km^2 and includes six tributaries: Fos Grant, Rio Crede, Rio Prestalla, Rio del Croz, Rio delle Giare and Fos Maestro (Fig. 1). Among the six tributaries, Fos Grant (average flow of approximately 0.1 m^3/s with rapid increases up to 1 m^3/s following intense rain events) contributes up to 70% of the total water input. With the outlet (Torrent Silla) located in the south-western part of the lake, the water balance results in a hydraulic residence time of about one year. A small daily withdrawal of a maximum of 0.2–0.3 m^3/s for hydropower production is balanced by the inflow from the upstream lake, Lake le Piazze. The water intake for hydropower is located in the northern part of the lake and consists of a vertical pipe located approximately 1.70 m above the lake floor. Field measurements showed that this water withdrawal does not significantly affect the circulation regime of the lake, with no short-circuit effect visible on the NE–SW currents, nor entrainment and re-suspension phenomena of the cohesive benthic sediment (Righetti and Lucarelli, 2010).

At the end of the 90s, increased agricultural activity (small fruits cultivation) and animal farming (mainly horses) near Lake Serraia resulted in an increased diffused nutrient loading which promoted anthropogenic induced eutrophication. Highly influenced by its shallow waters and long hydraulic residence time, the trophic state of Lake Serraia evolved from mesotrophic to eutrophic with phosphorus (P) being the limiting nutrient for lake algal productivity. Based on time series measurements between 2000 and 2005, the