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Evidence from field measurements and satellite imaging of impact of Earth rotation on Lake Iseo chemistry

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ABSTRACT

During an initial field survey in 2012, we observed an unexpected asymmetry of dissolved oxygen distribution between the western and eastern side in northern Lake Iseo. Motivated by this apparent anomaly, we conducted a detailed field investigation, and we used a physical model of the northern part of the lake to understand the influences that might affect the distribution of material in the northern section of the lake. These investigations suggested that the Earth's rotation has significant influence on the inflow of the lake's two main tributaries. In order to further crosscheck the validity of these results, we conducted a careful analysis at a synoptic scale using images acquired during thermally unstratified periods by Landsat-8 and Sentinel-2 satellites. We retrieved and post-processed a large set of images, providing conclusive evidence of the role exerted by the Earth's rotation on pollutant transport in Lake Iseo and of the greater environmental vulnerability of the north-west shore of this lake, where important settlements are located. Our study confirms the necessity for three-dimensional hydrodynamic models including Coriolis effect in order to effectively predict local impacts of inflows on nearshore water quality of medium-sized elongated lakes of similar scale to Lake Iseo.

Introduction

The growing anthropogenic stress exerted on many lakes in the world (e.g., Wetzel, 1992; Özkundakci et al., 2014) motivates concern for their endangered trophic states. In Europe, the Water Framework Directive (European Parliament, 2000) requires that water bodies be returned to a condition as close as possible to their natural status. This ambitious task might be very challenging, particularly for deep lakes that are usually characterised by long water renewal times. In the case of Lake Iseo, a deep Italian prealpine lake, the theoretical renewal time is 4.5 years but its actual value is 60% longer due to the thermal stratification of the lake during most of the year (Pilotti et al., 2014b). The renewal time is expected to increase further due to the effects of climate change (Pilotti et al., 2014b). The lake's trophic reference condition dates back to 1967 (Bonomi and Gerletti, 1967), when two vertical profiles of physical and chemical properties in spring and winter showed that the lake was oligotrophic with oxygen concentrations of about 8 mg/l at the maximum depth of 250 m. In contrast, we recently observed during several field campaigns that the current situation is characterised by hypoxia below 80 m and total anoxia below 110 m. Such a dramatic evolution should stimulate concern. Although several countermeasures to limit nutrient inputs have been introduced and a combined sewer has been operating for the last 15 years along the lake's periphery, the sewage from the lake's large watershed is still partly untreated and the average concentration of phosphorus in the lake is not decreasing. Similar to other cases (e.g., Chen et al., 2004; Chen and Driscoll, 2009; Halder et al., 2013; Chomicki et al., 2016), in Lake Iseo the preponderance of the watershed loading enters from the tributaries with high concentrations of dissolved and particulate matter, nutrients and bacterial pollution during rainy periods when combined sewer weirs overflow into the tributaries. The distribution of these waters in the epilimnetic layer could trigger local algal blooms and exceed maximum permissible pathogen levels for bathing. The spatial distribution of tributary waters is also critical to understanding the current rate of oxygen supply and demand in the intermediate layer between the anoxic bottom and the fully oxygenated surface layer (Fink et al., 2016). Thus, understanding the interplay of the lake's hydrodynamics with the inflows is critical to predicting water quality impacts on this system.

In order to explore these issues in Lake Iseo, an initial campaign monitoring temperature, oxygen concentration, conductivity, turbidity and chlorophyll-a (Chl-a) was conducted in 2012. A more detailed monitoring campaign was replicated in the summer 2014. This latter survey, which collected data at 179 sites, focused on the northern part of the lake to measure physical parameters in the layer between the surface and the depth of 70 m. The large data set was eventually used to

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reconstruct the spatial pattern of the measured variables. In order to fully exploit the data's information content and to provide more representative visualization than the usual two-dimensional (2D) horizontal and vertical contoured sections, three-dimensional (3D) surfaces were generated with an interpolation technique based on Inverse Distance Weighting (IDW). This involved pre-processing the data using a vertical expansion in order to effectively deal with the anisotropy between vertical and horizontal directions caused by thermal stratification.

The reconstructed 3D surfaces exhibited a marked east-west asymmetry of the parameters distribution, that must reflect some dynamic physical processes. We advance the hypothesis that a primary role is played by the Earth's rotation, combined with bacterial respiration of organic matter conveyed by river-borne intrusions that exceed the oxygen inputs of river water. The net result is an overall negative impact on metalimnetic and hypolimnetic oxygen concentrations (e.g., Chapra, 1997; Bouffard and Perga, 2016). Two mechanisms support this hypothesis. First, during the thermally stratified period, the westward deflection of the two main tributaries flow could be affected by shoretrapped internal Kelvin waves moving cyclonically around the lake (Valerio et al., 2012). Whereas the effect of internal Kelvin waves in very large lakes is restricted to the area adjacent to the shore (Mortimer, 2006, documented a fall to about 2% at a distance of four internal Rossby radii in Lake Michigan, defined as the ratio between the non-rotating phase speed to the inertial frequency), in Lake Iseo Kelvin waves must occupy the whole basin. However, the effectiveness of this mechanism should be hindered by the fact that the orbits of the water particles involved in internal Kelvin waves in deep waters should be closed, so that the net drift in the direction of phase propagation would be negligible. Moreover, when wind is weak or when the lake is thermally unstratified, (i.e., from December to April), internal wave forcing is absent.

The second mechanism that can be invoked is the action of the Earth's rotation on the plume of the entering tributaries (e.g. Griffiths, 1986), which acts permanently to deflect the inflow when the plume's inertia is small compared with the Coriolis force. The relevance of Coriolis force on the river-induced circulation has been shown for large lakes through physical models by, *inter alia*, Rumer and Robson (1968) in Lake Erie, by Li et al. (1975) and Atkinson et al. (1994) in Lake Ontario and by Stewart (1988) in Lake Constance. The effects of Coriolis force were also documented in medium size lakes by Hamblin and Carmack (1978) in Kamloops Lake, and by Morillo et al. (2008) in Coeur d'Alene Lake. In addition, it is mentioned by Laborde et al. (2010) in Lake Como, whose width is comparable to that of lake Iseo and where the river is deflected towards its right-hand shoreline irrespective of wind conditions. The correspondence between sedimentological units in lakes and Coriolis-related currents has been observed in the past by several authors (e.g., Wright and Nydegger, 1980; Hamblin and Carmack, 1978; Hakanson and Janson, 1983) and is also related to the deposition of river-borne pollutants (Hakanson, 1974). This hypothesis was supported by the results of a physical model in Froude and Rossby similarity (Pilotti et al., 2014a), that, however, explored a limited range of Reynolds numbers and did not take into account the direct action of wind forcing. Although an alternating daily wind regime is usually present on this lake (Pilotti et al., 2013), we decided to focus on the permanent effect of the Earth's rotation, that, in thermally stratified periods, is superimposed on the wind-generated internal waves (see also Pilotti et al., 2014a).

The use of satellite images in the current study provided additional insight into the inflow's dynamics. Satellite remote sensing has been often used in limnology (e.g., Lathrop et al., 1990; Chipman et al., 2004; Li et al., 2008; Zhang et al., 2016) and here is used along with images provided by a land-based webcam. We monitored the influence area of the tributaries by enhancing the signal related to turbidity (e.g., Vanhellemont and Ruddick, 2014), according to the algorithm suggested by Brando et al. (2015) operating with Landsat-8 OLI (Operationl Land Imager) data. This sensor provided a synoptic view of the study area with a pixel size of 30 m, that is adequate for observing local to regional scale processes. To visualize turbidity patterns at finer spatial resolution, higher spatial resolution images acquired from fixed webcam and Sentinel-2 data were also used. In particular, the 10 m spatial resolution of Sentinel-2 data is particularly useful for investigating the fine scale patterns of optical properties in inland waters (Toming et al., 2016). Our research clearly indicates that, for the purpose of this type of analysis, the observation period should be selected on the basis of the buoyancy of the inflowing waters with respect to the lake. If interflow is prevailing in a thermally stratified period (summer), remote observations do not provide useful evidence due to the intrusion of the tributary waters under the lake surface. On the other hand, images acquired during the thermally unstratified period highlight systematic evidence of a westward drift of the tributary waters, that, in turn, provides a confirmation of the greater vulnerability of the west coast of the lake with respect to the tributary pollutant loads.

Field site description

Although Lake Iseo has been monitored regularly since the end of the 1970s, previous sampling was primarily conducted at the deepest point along the lake axis just to the west of the large island, Monte Isola (Fig. 1). In the past, specific campaigns did not focus on the northern part of the lake or to study the actual spatial variability of water-quality parameters. In the following, we detail a set of techniques that we used to assess the role exerted by the Coriolis force on the distribution of waters entering from the two major tributaries at the north end of the lake.

Lake Iseo is located in the prealpine area of the Lombardy region (Fig. 1), has a maximum depth of about 256 m, an area of 61 km^2 and a volume of about 8 billion m^3 making it the fifth largest Italian lake in terms of volume. The lake drains a large watershed (1807 km^2) which is about 30 times larger than the lake surface area) and is also one of the most industrialised districts in the Italian Alps. The complex lake hydrodynamics have been previously studied by Valerio et al. (2012), Pilotti et al. (2014a, 2014b) and Hogg et al. (2013).

The Oglio river (inflow at point I1 in Fig. 1) and Canale Italsider (inflow at point I2 in Fig. 1), are the two main tributaries. They are partly fed by the largest Italian glacier (Adamello, 3554 m a.s.l.) and their overall average annual inflow is 55 m^3/s. Approximately 19 km before entering the lake (point J1 in Fig. 1), up to 40 m^3/s (and on average about 29 m^3/s) of Oglio waters are diverted to Canale Italsider and conveyed to a hydropower plant before being returned to the lake at I2. Accordingly, considering that the average value of the overall Oglio discharge which would be exceeded 347 days a year (Q_{347}) is 20.4 m^3/s, it is clear that during most of the year the discharge in the Oglio river downstream of the diversion J1 is limited to the ecological flow.

At the lake's inlet, waters conveyed by Canale Italsider are on average 2 °C colder than those conveyed by the Oglio river (see Fig. 2) and during the summer this difference can rise to 5 °C. Moreover, as shown in Fig. 2, the temperature of these two inflows is usually colder than the temperature of the lake surface but warmer than the lake hypolimnetic water (currently 6.6 °C below 220 m of depth). Accordingly, interflow is the dominant hydrodynamic condition of both these tributaries although during the end of winter they may occasionally flow on the lake surface.

A waste water treatment plant (WWTP) is located along the Oglio river (see symbol in Fig. 1), 900 m upstream of its inlet into Lake Iseo. During rainy periods, due to sewer hydraulic overcharge of the combined sewer, sewage is frequently delivered untreated to the river. In addition, about 30% of the sewage in Valle Camonica, the largest watershed (Fig. 1) is still discharged totally untreated, or only partly processed, into the river. Accordingly, the bacterial and nutrient pollution carried by the Oglio river is, at least occasionally, non negligible.

Two important historical settlements, Lovere and Pisogne (see Fig. 1), are located along the northern part of the study area. The city