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A fast-response methodological approach to assessing and managing nutrient loads in eutrophic Mediterranean reservoirs

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ABSTRACT

With many lakes and other inland water bodies worldwide being increasingly affected by eutrophication resulting from excess nutrient input, there is an urgent need for improved monitoring and prediction methods of nutrient load effects in such ecosystems. In this study, we adopted a catchment-based approach to identify and estimate the direct effect of external nutrient loads originating in the drainage basin on the trophic state of a Mediterranean reservoir. We also evaluated the trophic state variations related to the theoretical manipulation of nutrient inputs. The study was conducted on Lake Cedrino, a typical warm monomictic reservoir, between 2010 and 2011. We assessed the hypereutrophic condition of the reservoir by monthly samplings of the water column and compared these results with the amount of nutrient load originating from anthropic activities in the drainage basin [42.6 $\mathrm{t\,P\,y^{-1}}$ for total phosphorus (P) and 531 $\mathrm{t\,N\,y^{-1}}$ for total nitrogen (N)]. We verified how the predictive OECD management model could be confidently applied to predict the P concentration in the reservoir on the basis of estimated loads from the drainage basin (98.7 $\mathrm{mg\,P\,m^{-3}}$ assessed versus 101 $\mathrm{mg\,P\,m^{-3}}$ estimated, approximately 2.5% over). Different scenarios are presented showing how it is possible to reduce approximately 62% P and 43% N, altering the condition of the ecosystem to become more mesotrophic. We also propose some management strategies to improve water quality in this lake ecosystem.

1. Introduction

Over recent decades, increasing anthropogenic activities have led to the widespread nutrient enrichment of inland and costal waters, resulting in a range of environmental, social, and economic issues because of the degradation of water resources (Carpenter et al., 1998; Smith et al., 1999). Eutrophication is the most widely known and most common result of this hyperfertilization, especially in response to increases in nitrogen (N) and phosphorus (P) load (Vollenweider, 1968). It causes a state shift in water bodies that leads to the loss of environmental goods and services that they provide (Dodds et al., 2008). In fact, the quantity and quality of nutrient inputs to a water body can have profound effects upon its ecosystem processes and structure, acting, for example, on its biogeochemistry and biodiversity, and altering the water quality.

Eutrophication primarily concerns water bodies that receive nutrients in excess of a critical threshold, leading to uncontrolled vegetation growth with the resulting imbalance of the aquatic ecosystem (Smith et al., 1999). Eutrophication has many negative effects, among which one of the most worrying is the increased growth of microalgae (Assmy and Smetacek, 2009) and cyanobacteria (Paerl and Otten, 2013; Merel et al., 2013) that interfere with the use of the water (Jorgensen, 2001). Their blooms contribute to a range of problems, including fish kills, foul odors, unpalatability of drinking water, and the formation of tri-halomethane during water chlorination in treatment plants (Kotak et al., 1996).

The nutrient supplies to water bodies originate from different sources, such as external inputs, including drainage of the catchment area, groundwater, and the atmosphere, and internal inputs, such as release from sediments. The external nutrient supplies can be further divided into (i) point sources, which have a localized origin; and (ii) nonpoint sources, which originate from soil removal and are more difficult to monitor and regulate compared with point sources. The latter have been extensively categorized in terms of

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the different types of urban and industrial wastewaters, whereas nonpoint sources can be generally classified in relation to different land uses (Carpenter et al., 1998). More recently, an intermediate category was also proposed, which includes overflows from septic systems, seepages from farmyards, or road and/or track runoff (Edwards and Withers, 2008).

Given that P and N are recognized as the most crucial limiting nutrients for lake productivity (Wetzel, 2001; Phlips, 2002), many models focus on determining their concentration to define the trophic status of an aquatic ecosystem and to predict the quality of aquatic resources. One of the most important issues is determining the crucial level of nutrient concentrations that, if exceeded, would tip a lake ecosystem into a degraded state (Vollenweider, 1976a). Various approaches to evaluate the amount of nutrients from the different sources have been developed (Johnes, 1996). Some of these models are based on nutrient export coefficients (OECD, 1982; Beaulac and Reckhow, 1982). In an export coefficient approach, nutrient loads are evaluated as a function of the export of nutrients from each source in the catchment toward a lake. In addition, Vollenwider's model (OECD, 1982) linked external inputs and water body nutrient concentrations in the evaluation of the mass balance of N and P, in relation to the morphometric and hydraulic characteristics of the lake.

Model approaches are particularly relevant to any environmental quality assessment or management of water bodies, and represent a key feature in predicting future trends or developing restorations plans for eutrophic systems (Smith, 1998). A model approach also represents a useful tool to address the worsening of eutrophication resulting from the effect of rapid climate change (Dokulil and Teubner, 2011; Jeppesen et al., 2010). Moreover, in the Mediterranean basin, water quality deterioration resulting from eutrophication is also accompanied by a reduction in water resources and increases in requests for different uses, e.g. agriculture (Iglesias et al., 2007; Garciía-Ruiz et al., 2011).

Here, we present a catchment-based approach to identifying and estimating the direct effect of external loads originating in the drainage basin on the trophic state of a Mediterranean reservoir. Theoretical scenarios of trophic state are then simulated by the manipulation of the nutrient inputs, to improve the lacustrine water quality of the lake.

2. Materials and methods

2.1. Study area

Lake Cedrino resulted from damming of the Cedrino River in 1984. The lake is located in central-eastern Sardinia (western Mediterranean, Italy; Fig. 1). It has a surface area of 1.5 km^2 and a volume of approximately 20×10^6 m^3 when filled to the maximum (103 m a.s.l.), and a mean depth of 26.5 m. The lake has a dendritic shape and runs for approximately 8.5 km in the old bed of the Cedrino River (main tributary), and for approximately 2.4 km along the Flumineddu River. The catchment covers approximately 630 km^2 with approximately 50,000 inhabitants. The hydrogeological basin that feeds the lake comprises Middle Jurassic–Upper Cretaceous dolostones and limestones covering a crystalline Palaeozoic basement composed of granites and metamorphic rocks. According to ECOSTAT (2003, 2004), Lake Cedrino belongs to the LM7 category (i.e., altitude <800 m a.s.l., mean depths >15 m, conductivity <2.5 mS cm^{-1}).

Given the availability of long-term data relating to Lake Cedrino, the lake has been part of the '10 Sardinian Lake Ecosystems' of the Italian long-term ecological research network (http://www.lteritalia.it) since 2006. The lake has been in a eutrophic state since it was first filled, with high chlorophyll *a* concentrations, massive blooms of cyanobacteria, hypolimnetic oxygen depletion, low water transparency, and siltation of the lake bed (Padedda and Sechi, 2008).

The regional agency Ente Acque della Sardegna (ENAS) has been the manager of Lake Cedrino since 2006.

2.2. Sampling strategy and analyses

A survey on an annual cycle was carried out to define the environmental condition and to correlate the trophic status of Lake Cedrino to the theoretical nutrient loads.

Sampling was conducted on a monthly basis from September 2010 to August 2011 at one station close to the deepest part of the lake (Fig. 1). It was not possible to sample in November because of adverse meteoclimatic conditions. Samples were collected at fixed depths using a Niskin bottle along a vertical profile from the surface (0.5 m), from depths of 1, 2.5, 5, 7.5, 10, 15, and 20 m, and below the latter depth at intervals of 10 m to the lake bottom. Temperature, pH, and dissolved oxygen were measured in the field using a multiparametric probe (YSI model 6600 V2, Yellow Springs, OH, USA). Transparency was assessed by Secchi disk (SD) measurements.

Water samples were stored in cold, dark conditions before laboratory analyses, which were done within 24 h of collection. We evaluated ammonium (NH_4), nitrate (NO_3), nitrite (NO_2), total nitrogen (TN), orthophosphate (RP), and total phosphorus (TP), according to Strickland and Parsons (1972), and chlorophyll *a* (Chl*a*) as described by Goltermann et al. (1978).

2.3. Water balance

Water balance was calculated on a monthly basis for the hydrological year from September 2010 to August 2011 and related to the meteorological data (monthly averages of temperature and cumulative rainfall) and water volumes data of the reservoir by ENAS.

The monthly water balance of Lake Cedrino was calculated based on Eq. (1):

$$St_n = St_{n-1} + Iw_n - Ev_n - Hy_n - Dr_n - Ir_n - Sp_n \quad (1)$$

where *St* is the water stored in the month *n*, *Iw* is the water input from the drainage basin, *Ev* is the evaporation, *Hy* is the water volume drawn for hydroelectric uses, *Dr* for drinking uses and *Ir* for irrigation, and *Sp* is the discharge for spilling. In Eq. (1), positive values indicate that water flows into the lake, whereas negative values imply that water leaves the lake.

2.4. Nutrient load calculations

The calculation of nutrient loads was accomplished by multiplying the specific coefficient (Table 1) to the unit amount of the related point [waste waters from urban centers (UW), industry (IW) and livestock (LS)] and nonpoint [urban areas (UA), agricultural (UAA), natural and seminatural and urban areas (NsNA)] sources. Nutrients loads were attributed to each municipality.

2.4.1. Nonpoint sources

To explore the land uses of the drainage basin (629.7 km^2), spatial data processing was performed with the support of a geographic information system. The analysis focused on the evaluation of land cover using techniques of classification to generate polygons by clipping the shape of the most recent land-use map (RAS, 2008) and by automatic classification of digital images of medium spatial resolution (1:25,000). The automatic segmentation was carried out on two levels: a preliminary level on the whole area of the drainage basin of Lake Cedrino and a second level on the different municipality areas that fell within the drainage basin. Each segmentation analysis was measured to obtain objects in accordance with the