Science of the Total Environment 541 (2016) 683–691

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Cooling and eutrophication of southern Chilean lakes

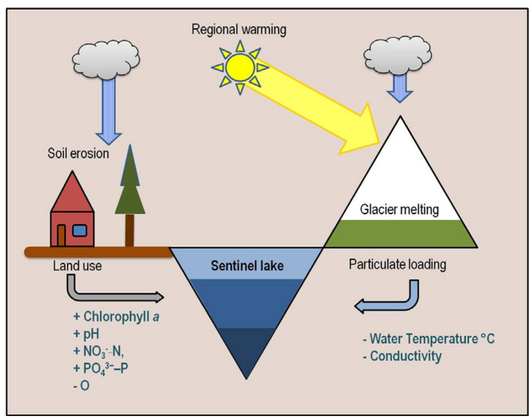
Jaime Pizarro [a,*], Pablo M. Vergara [b], Sergio Cerda [a], Daniela Briones [a]

[a] Departamento de Ingeniería Geográfica, Facultad de Ingeniería
[b] Departamento de Gestión Agraria, Universidad de Santiago de Chile, Av. Lib. B. O'Higgins 3363, Santiago, Chile

HIGHLIGHTS

- We studied water parameters of ten Chilean lakes over two decades
- The lakes exhibited a temporal decrease in temperature and conductivity
- Nutrient load increased in all lakes
- Water quality may respond to regional climate and land-use change

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 28 July 2015
Received in revised form 7 September 2015
Accepted 20 September 2015
Available online xxxx

Editor: D. Barcelo

Keywords:
Eutrophication
Central-southern Chilean lakes
Land use
Temporal trends

ABSTRACT

Understanding the impacts of global warming and human-disturbances on lakes is required for implementing management strategies aimed at mitigating the decline of the quality and availability of water for humans. We assessed temporal trends in water parameters, and the contribution of land use to the eutrophication of the largest lakes of central-southern Chile. The mean values of water parameters varied seasonally, with lakes Chapo and Caburgua exhibiting lower pH, temperature, and N/P ratio values. Over the assessed period (19 years), we found a temporal reduction in water conductivity and temperature of the lakes. The concentration of NO_3^--N, PO_4^{3-}–P and dissolved oxygen increased in all the lakes, but pH increased in eight out of the ten lakes. The negative temporal trend in temperature was more pronounced as the depth level increased. Lakes whose basins had a higher percentage of forest plantation and urban areas had larger values of Chlorophyll a and pH, as well as, smaller values of dissolved oxygen. Lakes whose basins included larger percentages of native forest had smaller nutrient (NO_3^--N, PO_4^{3-}–P) concentrations. Our findings suggest that decreased rainfall in central-southern Chile due to climate change may cause a decrease of particulate material that is carried by tributaries into the lakes. The observed temporal decrease in temperature, especially at the deeper levels, may be explained by the rapid melting of glaciers. Although the studied lakes are classified as oligotrophic, deforestation and expansion of urban areas around the lakes have led to increased nutrient input, thus accelerating their eutrophication.

1. Introduction

Sentinel lakes provide mid- and long-term information on biogeochemical changes derived from natural and anthropogenic disturbances. Understanding the impact of global warming and human-disturbance on sentinel lakes is required for implementing management strategies aimed at mitigating the decline of water quality and availability to humans (Adrian et al., 2009; Bonsch et al., 2015).

The deterioration of water quality in lakes due to urban pollution and agriculture is of increasing concern to human populations and

* Corresponding author.

http://dx.doi.org/10.1016/j.scitotenv.2015.09.105
0048-9697/© 2015 Elsevier B.V. All rights reserved.

ecosystem health (Rabalais, 2002; Bonsch et al., 2015). Despite the development of effective techniques for mitigating point source pollution in lakes and rivers, the control of non-point sources is still an unsolved problem (Arheimer et al., 2004; Ripa et al., 2006). Non-point and point sources of pollution contribute to eutrophication and physico-chemical changes of freshwater ecosystems through the discharge of nutrients (NO_3^--N, PO_4^{3-}–P). Eutrophication occurs as an accelerated process in coastal waters and freshwaters of densely populated regions (e.g., Sharpley et al., 1999; Nixon, 1995; Smith et al., 2006). Eutrophication reduces the oxidative capacity of subsurface water by promoting the formation of an anoxic zone while resulting in a chemical stratification of the water column (Müller et al., 2012). These environmental conditions lead to the blossoming of cyanobacteria whose toxins cause liver damage in animals and humans (Paerl and Paul, 2012).

A variety of physical, chemical, and biological parameters can be used as proxies for eutrophication in lakes, reservoirs and rivers (Müller et al., 2012). Chlorophyll *a* is a widely accepted parameter for estimating the trophic state of lakes (Søndergaard et al., 2011) and defining the levels of nutrient loading (Dillon and Rigler, 1974; Vollenweider, 1976; Kasprzak et al., 2008; Janse et al., 2010; Wu and Malmstrom, 2015). Variation in pH can be promoted by eutrophication and human activities influencing water acidification, thus providing relevant information about water quality (Driscoll et al., 2007; Jeschke et al., 2013). Although nutrients (N and P) are key determinants of eutrophication in lakes, a steady increase in water temperature also promotes algal primary productivity (Van Vuuren et al., 2010; Xia et al., 2015). Global warming can disrupt chemical processes of water such as adsorption/desorption rates of metal species, water salinity, and the amount of rainfall that reaches lakes (Schlesinger, 1997; Battarbee et al., 2005; Li et al., 2015). Variations in thermal conditions can affect the trophic state of deep lakes, not only by promoting algal productivity, but also by vertical mixing that mobilizes nutrients from deep waters (Goldman et al., 1989). Consequently, an increase in water temperature resulting from global warming may favor the bloom of algae (Bouraoui et al., 2002; Whitehead et al., 2009; Paerl and Huisman, 2009). Therefore, quantifying changes in physical and ecological parameters is of importance for understanding the eutrophication processes in lakes (Schindler, 2006).

Central-southern Chile includes several monomictic and oligotrophic lakes, characterized by low concentration levels of chlorophyll *a* and high transparency (Soto and Campos, 1995; Soto, 2002). Previous studies addressing the physical, chemical, and biological conditions of lakes in southern Chile and Argentina have suggested that primary productivity in these lakes is primarily limited by N rather than by P concentrations (e.g., Soto and Campos, 1995; Baigun and Marinone, 1995; Soto and Stockner, 1996; Soto, 2002; Diaz et al., 2007). A potential N limitation in these lakes has been attributed to water transparency and to reduced inputs of inorganic nitrogen from small-unperturbed watersheds (e.g., Soto, 2002; Xia et al., 2015). Although the primary productivity and eutrophication of the central-southern Chilean lakes may respond to N limitation, these processes could also be affected by increased nutrient load from intensive human land use as well as by changes in the thermal conditions of the water resulting from global warming. A previous study suggests that changes driven by anthropogenic causes are responsible for a positive temporal trend in the nutrient load of southern Chilean rivers, a pattern relatively common in fresh water bodies worldwide (Li et al., 2009; Pizarro et al., 2010). In particular, the fast economic development and human population growth in this region has resulted in extensive conversion of native forests in forest plantations, agricultural, and urban areas (Echeverría et al., 2006; Pizarro et al., 2014; Table 1). Despite the rapid loss of native vegetation and increased glacial melting resulting from climate change, the southern Chile region still lacks landscape-planning strategies intended to reduce nutrient load in natural waters (León-Muñoz et al., 2013; Pellicciotti et al., 2014). However, since the basins (i.e. the area surrounding and draining into the lakes) of central-southern Chilean lakes differ in their land use (Table 1), the physical and chemical characteristics, nutrient load, and primary productivity of these lakes should change according to the magnitude of these anthropogenic changes.

In this study we addressed the following questions:

i) Are central-southern Chilean lakes homogeneous in physical, chemical, and biological parameters associated with the eutrophication of the lakes?
ii) Are there temporal trends in water quality parameters over the last two decades?
iii) What human land uses have a greater contribution to eutrophication of the central-southern Chilean lakes?

2. Methods

2.1. Studied lakes

We studied ten different lakes of central-southern Chile, which represent the largest freshwater lakes of this region (from 37° 55′ to 41° 27′ S lat. See Fig. 1; Table 1). Local meteorological conditions occurring over the basins of these lakes is relatively similar, with mean annual precipitation ranging from 1800 mm to 2900 mm. Soils are of volcanic origin, with physical properties that are relatively similar between lake basins (Zunino and Borie, 1985; Pizarro et al., 2003). All these lakes have oligotrophic characteristics (Soto, 2002). We characterized land use cover in each lake basin using a GIS land use-vegetation database (CONAF-CONAMA-BIRF, 2000), which allowed us to identify polygons representing the main land use activities at the landscape scale (Table 1). From this analysis we determined variation in land use patterns among the different lake basins (Table 1). Five out of ten lakes have more than 50% of native forest within their basins, while the fraction of basins with agricultural and urban areas is relatively low in all the lakes (Table 1). However, livestock pasture is the major land use practice in these basins, comprising from 0.14 to 52.3% of the basin area (Table 1).

Table 1
Summary of information about the studied lakes and land use characteristics (percentage of land cover as shown in Fig. 1).

Lake	Altitude (masl)	Area (km^2)	Depth (m)	Stations (n)	Land use pattern (%)						
					Native forest	Forest plantation	Agriculture	Open areas	Wetlands	Pasture	Urban
Caburgua	300	53	327	3	89.9	0.02	0	0.03	1.17	8.84	0.01
Calafquén	209	120	212	3	38.6	0	0	4.24	14.52	41.31	1.33
Chapo	240	55	230	3	98.6	0	0	0.67	0.6	0.14	0
Llanquihue	50	878	317	4	53	0.01	0.03	1.63	5.16	40.12	0.04
Maihue	128	50	207	2	90.4	0	0.15	0.13	5.38	3.91	0
Panguipulli	140	117	268	3	83.5	0.03	0	0.02	1.17	15.26	0.01
Ranco	70	423	199	3	43	0.01	0.29	1.89	2.55	52.29	0.01
Riñihue	116	78	323	3	81.3	0.04	0	0	1.93	16.7	0
Todos Los Santos	181	189	337	3	95.3	0	0.05	2.74	1.58	0.3	0
Villarrica	220	176	165	4	59.4	0.22	0.02	1.28	3.17	35.78	0.1