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Water bodies quality assessment and trophic gradient monitoring of the Llanquihue lake-Maullin River in Chile from years 1999-2014

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Abstract

The atmospheric and anthropogenic stressors and their impact on trophic states of the Chilean northern Patagonian lakes need the assessment of interconnection between land-based drivers, the potential pressures, and effects. Achieving this goal requires adequate contemplating on the social and economic factors that influence decision-making around land-lake—further affecting the management of nutrients, pollutants, and their impact on the lake ecosystem components. The present study aims to explain the environmental health state of Llanquihue lake, a large lake in northern Chilean Patagonia and Maullin River, based on a statistical analysis of data obtained from the Directorate of Water in Chile from years 1999-2014. The data evaluated shown that the Llanquihue Lake and the Maullin River water quality influenced by the nutrient increase and transparency decrease in the tropical freshwater of this study. In the Chilean lakes of Patagonia, there do not seem to be any studies based mainly on ecosystem management approaches to human activities that will affect the water column, pelagic waters seabed, diversity, and others. Anyways, it is a proven fact that these problems need` in-depth knowledge of a higher sort of earth science, social science, economic, and biological variables, and others.

1. Introduction

Lake's degradations are an important topic at world level, one of these degradation processes is eutrophication, that is an increase of nutrient inputs from the surrounding basin with consequent phytoplankton productivity increase, and anoxia generation with consequent water quality detriment [1]. Eutrophication control is important world: eutrophication management is vital for water quality management, specifically in terms of toxic algal blooms control that can affect the surrounding environments and associated activities, such as water sources for different human consumption, or for agricultural activities, or recreational uses [1,2].

These changes are originated from human alterations in their surrounding basins, thus individually changing soil uses [2, 3], then generating alterations in nutrients inputs from the surrounding to the water body. However, the modification consequently increases the phytoplankton activities including bacterial organic matter decomposition, anoxia generation, and other drastic environmental consequences such as biodiversity disturbance and fish mortality [2, 4].

Eutrophication, Global variability drive over the world's lakes: the eutrophication process, in pelagic environments, can generate first alterations in phytoplankton, because due to the nutrient inputs will change the phytoplankton assemblages, under oligotrophic situations the diatoms are abundant [5], that is replaced gradually by green algae under mesotrophic environments [6], and cyanobacteria under eutrophic condition [7]. In consequence, this generates an expansion of bacterial activities due to the organic matter, which raises its bacterial decomposition [8].

The zooplankton changes under eutrophic environment these fluctuations because there are very few species [8], and tolerant of high phytoplankton activity because some phytoplankton species of eutrophic environments have filamentous that can generate mechanical damage in zooplankton, or produce lethal toxins. For fishes, the situation can be more drastic because the anoxia condition can create massive death populations [9].

In this scenario, under severe eutrophication, human well-being, and its activities can be altered, such as decreasing of fisheries activities, bad quality of water sources for tourism, aquaculture, agricultural, and domestic uses [10] that would require more additional cost for expensive other previous treatments [11]. Integrated Environmental Management (IEM) considers the management of such as complex environmental issues using a holistic and inclusive approach [12]. The approach employs a list of steps that are logically ordered taking into consideration the complexities, multi-facetedness and inter-connectedness of the environmental issues to be addressed to achieve the best outcomes [13, 14].

Chilean Lakes trophic status: the Chilean Patagonian lakes are characterized by their marked oligotrophy (39º 00' - 41º 00'S / 71º 40' – 72º 40' W; 45 - 870 km^2 surface; 145 – 337 m as maximum depth; 0.32 – 1.10 μg/L chlorophyll a) [15, 16], a similar situation has been observed for Argentinean Patagonian lakes [17]. These lakes initially have a native forest in their surrounding basins that were replaced gradually by any kind of human activities, such as towns, agricultural and industrial zones [18, 19, 20, 21, 22].

The northern Patagonian lakes (Fig. 1), are characterized by their original oligotrophic status. Thus, during the last three decades of partial changes in the mesotrophic state due to alterations in the soil of the surrounding basins combined to the aquaculture activities [15, 16, 17, 20, 21, 22]. In these scenarios, changes have been observed in pelagic environments, because under original oligotrophic status there are mixotrophic ciliates as producers and few grazing zooplankton species. In contrast, under mesotrophic condition, mixotrophic ciliates are replaced by phytoplankton and zooplankton are characterized by zooplankton increasing species number [15]. Many of these lakes currently have numerous bays with human interventions such as towns, industrial zones, and salmon fish farming, that generate nutrients increasing, with consequent in phytoplankton activity and changes in zooplankton communities [18, 24].

In this context, Llanquihue Lake has many interests for use due to the presence of many human populations [24]. In this scenario, it would be necessary to make a multidisciplinary approach to study eutrophication management with the aim of decrease potential environmental damage due to human activities [25]. This paper aims to evaluate the water bodies quality and examine the northern Patagonian lakes trophic status in the context of these issues, using as a case study the Llanquihue lake.

2- Material and Methods

Study Area: Llanquihue lake is one of the 20 lentic representative freshwater ecosystems of central and southern Chile (41º 08'S 72º 47' W; 870.5 km^2 surface; 336 m as maximum depth; Table 1, Figs 1 and 2), this zone has a rainy temperate (41° S) weather [26], its outlet is the Maullín River, which flows into the Pacific Ocean. Llanquihue lake is located at 41° S (Fig. 2) and considered as the second most big lake in Chile. Its importance due the towns and industries in its basin, it has numerous bays with cities such as Puerto Varas, Llanquihue, Frutillar, Puerto Octay, bays with aquaculture activities such as Puerto Phillippi and Puerto Rosales, and zones with low human intervention such as Ensenada Bay and its surrounding [22]. In this context, the bays of this lake have a full trophic gradient, expressed in changes in pelagic communities [18, 22].

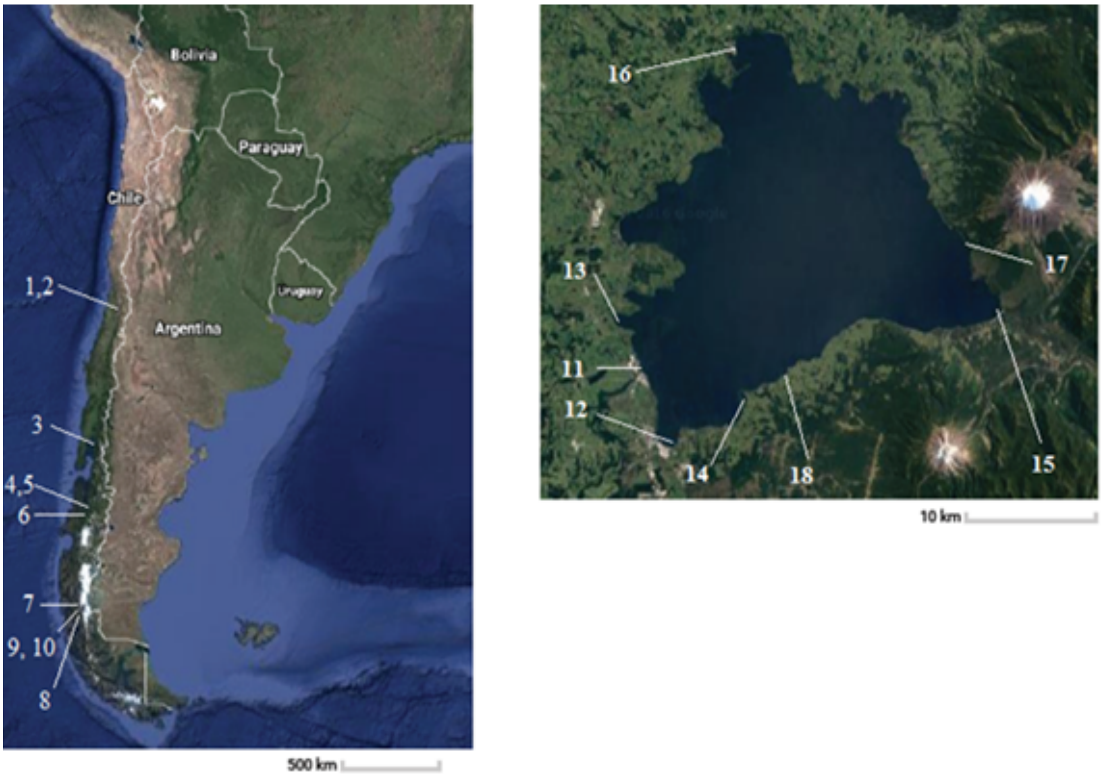

Figure 1. Map with some representative Chilean lakes and lagoons (Source: Google Earth, 2016): 1) Left: lakes along Chilean territory (1: Peñueñas; 2: Runge; 3: Llanquihue; 4: Los Palos; 5: Escondida; 6: Riesco; 7: Del Toro; 8: Sarmiento; 9: Gemela Este; 10: Gemela Oeste). 2). Right: sites in Llanquihue lake (11: Llanquihue town; 12: Puerto Chico; 13: Puerto Phillippi; 14: Puerto Rosales; 15: Ensenada; 16: Puerto Octay; 17: Volcanes bay; 18: Venado beach).

Also, Llanquihue Lake has introduced salmonid populations that are an essential resource for sports fisheries [27]. In this context, Llanquihue Lake would be an interesting scenario for multidisciplinary studies about eutrophication Integrated Environmental Management (IEM), considering its heterogeneity in human intervention due towns, agriculture in some bays and aquaculture activities in few bays [18]

Data analysis: the trophic state of water bodies was considered from surface, latitude maximum depth (Zmax), temperature, conductivity, pH, N-NO_3^-, N-NO_2^-, N-NH_4^+, P-PO_4^{-3}, dissolved oxygen (mg/L), chlorophyll concentrations (mg/L) and oxygen saturation data from years 1999-2014, from "Dirección General de Aguas-Chile" (www.dga.cl). It was managed based on average of data for each site considering the irregularity frequency.

Figure 2. Map of studied site: Sites in Llanquihue lake (1: Ensenada Bay; 2: Frutillar; 3: Puerto Octay; 4: Puerto Varas; 5: Zmax; 6: Río Maullín). (Source: Google Earth, 2016)

Table 1. Chemical parameters and trophic status for differents sites in Llanquihue Lake and Maullin River.

	DIN (mg/L)	PPO4 (mg/L)
Ensenada (n= 98)	0.058 ± 0.052	0.004 ± 0.003
Frutillar (n= 89)	0.057 ± 0.048	0.004 ± 0.002
Puerto Octay (n= 86)	0.061 ± 0.059	0.004 ± 0.005
Puerto Varas (n= 86)	0.057 ± 0.055	0.004 ± 0.002
Zmax (n= 12)	0.032 ± 0.007	0.004 ± 0.001
Maullin River (n=2)	0.029 ± 0.007	0.008 ± 0.006
	Ch. Ox. Dem. (mg/L)	Temp. ° C
Ensenada (n= 98)	10.571 ± 13.576	13.176 ± 2.884
Frutillar (n= 89)	8.618 ± 9.767	13.433 ± 2.813
Puerto Octay (n= 86)	10.214 ± 12.921	13.410 ± 2.924
Puerto Varas (n= 86)	10.750 ± 12.815	13.508 ± 2.737
Zmax (n= 12)	1.250 ± 0.449	12.040 ± 3.431
Maullin River (n=2)	5.875 ± 6.894	10.490 ± 0.085
	% Oxygen Sat.	Chl. "a" (ug/L)
Ensenada (n= 98)	93.502 ± 6.164	0.696 ± 0.608
Frutillar (n= 89)	96.690 ± 4.934	0.862 ± 0.731
Puerto Octay (n= 86)	95.861 ± 5.602	0.861 ± 0.667
Puerto Varas (n= 86)	96.284 ± 4.814	0.815 ± 0.693
Zmax (n= 12)	98.800 ± 2.917	1.039 ± 0.849
Maullin River (n=2)	98.050 ± 2.616	0.984 ± 1.042
	pH	Diss. O_2 (mg/L)
Ensenada (n= 98)	7.393 ± 0.434	9.780 ± 0.718
Frutillar (n= 89)	7.483 ± 0.379	10.052 ± 0.733
Puerto Octay (n= 86)	7.431 ± 0.323	9.973 ± 0.716
Puerto Varas (n= 86)	7.554 ± 0.354	10.057 ± 0.725
Zmax (n= 12)	7.888 ± 0.287	10.668 ± 0.927
Maullin River (n=2)	7.410 ± 0.382	10.835 ± 0.219
	Conduct. (uS/cm)	Secchi (m)
Ensenada (n= 98)	85.427 ± 10.241	15.922 ± 3.375
Frutillar (n= 89)	86.088 ± 4.700	15.403 ± 4.022
Puerto Octay (n= 86)	83.558 ± 14.203	15.729 ± 3.935
Puerto Varas (n= 86)	85.130 ± 6.744	17.538 ± 5.206
Zmax (n= 12)	69.033 ± 21.146	20.000 ± 6.000
Maullin River (n=2)	87.950 ± 0.636	13.350 ± 5.162

In the first step, to determine the main grouping variables, principal component analysis to the obtained data matrix was applied. In a second step, to determine the potential effects of the mentioned variables on chlorophyll concentration, a multiple regression analysis was applied. Statistical analysis was applied using the software R [28], and HSAUR R-package [29].

3- Results and Discussions

Physicochemical characteristics of the Llanquihue lake: The correlation matrix (Table 2) revealed the presence of significant direct associations ($P < 0.05$) between transparency with pH, chlorophyll "a" with dissolved oxygen; chlorophyll "a" with oxygen saturation; dissolved oxygen, with pH; pH with Chemical oxygen demand (Ch. Ox. Dem); pH with conductivity; temperature with dissolved inorganic nitrogen (DIN); and Chemical oxygen demand (Ch. Ox. Dem) with dissolved inorganic nitrogen. Also, inverse significant correlations ($P < 0.05$) were found between transparency with dissolved inorganic nitrogen (DIN); transparency with conductivity, chlorophyll "a" with Chemical oxygen demand (Ch. Ox. Dem); dissolved oxygen with dissolved inorganic nitrogen (DIN); dissolved oxygen with conductivity; and dissolved inorganic nitrogen (DIN) with pH. For axis 1, the main contributor variables were all variables included in the present study, whereas for axis 2, the main contributor variables were temperature, oxygen saturation, and chlorophyll "a".

Table 2. Correlation matrix for variables in Llanquihue Lake.

	Transp.	Chl a	Oxy. Sat	D. Oxyg	pH	Conduct	Temp	Ch. Ox. Dem.
DIN	-0.91 (P=0.02)	-0.81 (P=0.09)	-0.76 (P=0.13)	-0.94 (P=0.01)	-0.97 (P<0.01)	0.97 (p<0.01)	0.97 (p<0.01)	0.97 (p<0.01)
Ch. Ox. Dem.	-0.82 (P=0.08)	-0.88 (P=0.04)	-0.81 (P=0.09)	-0.95 (P=0.01)	0.96 (P=0.02)	0.96 (p=0.01)	0.95 (p=0.01)	
Temp	-0.85 (P= 0.07)	-0.73 (P=0.16)	-0.62 (P=0.26)	-0.86 (P=0.06)	0.97 (P=0.04)	0.97 (p<0.01)		
Conduct	-0.90 (P=0.04)	-0.85 (P=0.07)	-0.75 (P=0.14)	-0.93 (P=0.02)	0.99 (P=0.01)			
pH	0.95 (P=0.01)	0.88 (P=0.05)	0.87 (P=0.05)	0.98 (P<0.01)				
D. Oxyg	0.89 (P=0.04)	0.95 (P=0.01)	0.93 (P=0.02)					
Oxy. Sat	0.72 (P=0.17)	0.97 (P<0.01)						
Chl a	0.73 (P=0.16)							

The PCA (Figure 3, and Table 4) revealed the existence of one leading group joined by bays with towns (Puerto Varas, Puerto Octay and Frutillar), that have high chemical oxygen demand, temperature, conductivity, and dissolved inorganic nitrogen values. In contrast, the site with maximum depth has high transparency, pH, chlorophyll, and dissolved oxygen concentrations. Finally, Ensenada site (a place with low human intervention) has marked differences in comparison to the other sites.

Physicochemical characteristics of the Llanquihue lake and Maullin River: the correlation matrix (Tab. 3) revealed inverse associations between transparency with conductivity, chlorophyll "a" with dissolved inorganic nitrogen (DIN), chlorophyll "a" with chemical oxygen demand, oxygen saturation with chemical oxygen demand, dissolved oxygen with DIN. Whereas significant direct associations were found between transparency with pH, chlorophyll “a” with dissolved oxygen, chlorophyll “a” with oxygen saturation, oxygen saturation with dissolved oxygen, pH with conductivity, temperature with DIN, and chemical oxygen demand with DIN (Table 4).

For axis 1, the main contributor variables were all variables except transparency included in the present study. In contrast, for axis 2, the main contributor variables were temperature, conductivity, oxygen saturation, and pH (Table 4). The PCA (Figure 4, and Table 5) revealed the existence of one leading group joined by bays with towns (Ensenada, Puerto Varas, Puerto Octay, and Frutillar), that have high chemical oxygen demand, temperature, and dissolved inorganic nitrogen values. In contrast, Maullin river has high dissolved oxygen, low pH, and transparency. Finally, Zmax has high pH and openness.

Table 3 Correlation matrix for variables in Llanquihue Lake and Maullin river.

	Transp.	Chl a	Oxy. Sat	D. Oxyg	pH	Conduct	Temp	Ch. Ox. Dem.
DIN	-0.07 (P=0.89)	-0.83 (P=0.04)	-0.78 (P=0.06)	-0.97 (P < 0.01)	-0.47 (P=0.34)	0.42 (p<0.41)	0.93 (p<0.01)	0.87 (p<0.02)
Ch. Ox. Dem.	-0.43 (P=0.39)	-0.88 (P=0.02)	-0.82 (P=0.04)	-0.83 (P = 0.03)	0.78 (P=0.06)	0.77 (p=0.07)	0.65 (p=0.16)	
Temp	0.28 (P= 0.58)	-0.68 (P=0.13)	-0.62 (P=0.19)	-0.90 (P=0.01)	0.11 (P=0.83)	0.09 (p<0.86)		
Conduct	-0.87 (P=0.02)	-0.56 (P=0.25)	-0.50 (P=0.31)	-0.36 (P=0.48)	0.94 (P<0.01)			
pH	0.89 (P=0.01)	0.62 (P=0.18)	0.64 (P=0.17)	0.45 (P=0.37)				
D. Oxyg	0.02 (P=0.96)	0.91 (P=0.01)	0.89 (P=0.01)					
Oxy. Sat	0.24 (P=0.64)	0.97 (P<0.01)						
Chl a	0.22 (P=0.67)							

Table 4. Contribution of variables for PCA for variables in Llanquihue Lake.

	Axis 1	Axis 2
DIN	-0.343	-0.238
DQO	-0.342	-0.080
Temp	-0.323	-0.452
Conduct	-0.341	-0.214
pH	0.347	-0.006
D. Oxyg	0.348	-0.171
Oxy. Sat	0.306	-0.616
Chl a	0.321	-0.473
Transparency	0.321	0.228

The data evaluated indicated that, besides high chemical parameters including chemical oxygen demand, temperature, and dissolved inorganic nitrogen values in the Llanquihue Lake, the Maullin River water quality are influenced by the nutrient increase and transparency decrease in the tropical freshwater of this study.

Table 5. Contribution of variables for PCA for variables in Llanquihue Lake and Maullin river.

	Axis 1	Axis 2
DIN	-0.367	-0.228
DQO	-0.394	-0.046
Temp	-0.385	-0.424
Conduct	-0.287	-0.429
pH	0.310	-0.409
D. Oxyg	0.370	-0.257
Oxy. Sat	0.371	-0.074
Chl a	0.383	-0.089
Transparency	0.162	0.577

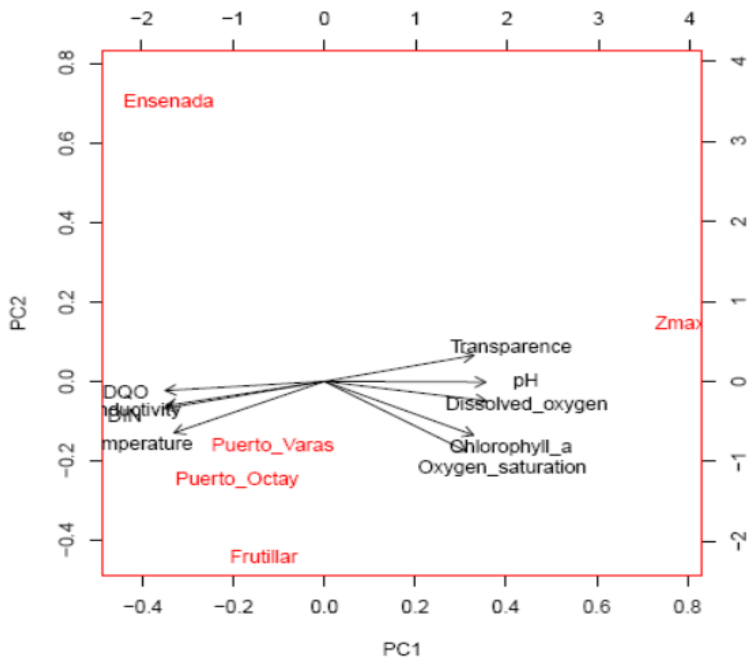

Figure 3. PCA result for the different sites in Llanquihue lake

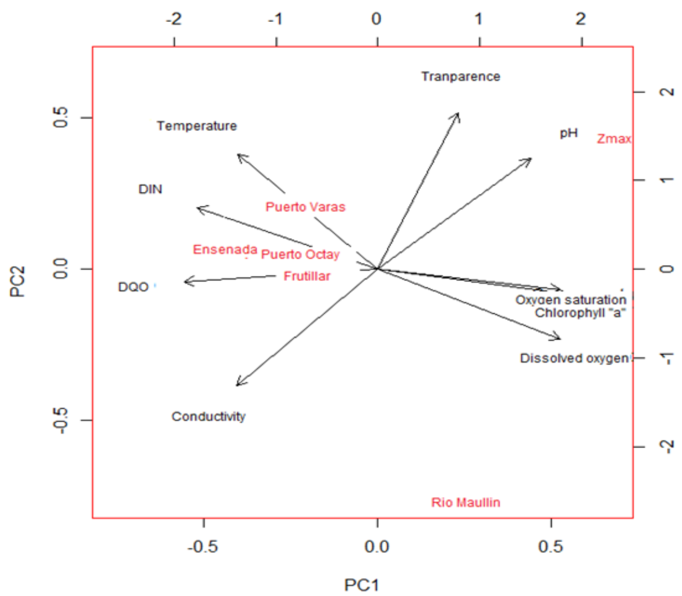

Figure 4. PCA results for the different sites in Llanquihue lake and Maullin River.

Furthermore, in a border scale, the water status in Llanquihue lake-Maullin River also can be influenced by seasonality and trophic state, with higher dynamic environments values observed in the rainy period, explained by Zmax with high pH, and transparency depending on the human discharge in the both « Lake-River ». The Chilean regulations about environmental topics, specify the primary norm, that is the level of ecological parameters for avoiding human health damage, whereas the secondary standard specifies the level of ecological parameters for avoiding environmental losses, these norms are specific for different sites (Ministerio del Medio Ambiente, Chile). Nevertheless, the legal Integrated Environmental Management depends on many public organisms such as particular departments of Chilean Navy and Chilean police forces, agriculture ministry, or fisheries sub-secretary. According to UNESCO « through the implementation of Integrated Water Resources Management (IWRM) principles, water has successfully been applied as a strategic input to the national economy and transferred from low-value to high-value uses. As a result, Chile provides an example of progress towards the three E's of IWRM: 'economic efficiency,' 'social equity', and 'environmental sustainability' » [30].

Nevertheless, the few studies on environmental topics on Chilean lakes are related to nutrients charges in shallow lakes with aquaculture activity, this study considered both natural and humans interviewed nutrients sources [23]. Nevertheless, it requires more regulations and applied studies for water resource management [31,32]. Based on nutrients balances, similar studies were done for urban wetlands in central Chile and then proposed specific management procedures for avoiding eutrophication and the consequent environmental damage [33,34]. In this context, it was proposed many management procedures on a multidisciplinary approach for protecting ecosystems associated with human intervention [35]. An environmental assessment or analysis could be a study of the environmental effects. It is often used within an Integrated Environmental Management planning process as a decision support tool to compare different options [32]. This approach has emerged in response to the requirement to develop a collaborative, interactive process to provide the holistic approach necessary for the successful sustainable environmental management [36].

Chile needs to integrate a new tool convenient with the water eutrophication issues, which causes enormous stress to the surface and deep biocenosis into its water management strategies for sustainable growth, incorporating adequate monitoring program to all policy-makers involved in national development planning with a new vision of necessary of a multidisciplinary approach [37]. The developing in the future of the complex patterns of trophic control to the overlap in "Lakes/Rivers/Pacific Ocean" boundaries relationship, assessment, and monitoring of the physical and -chemical water quality changes, linking the Integrated bottom-up and top-down effects, stimulating a complex long-term change in ecosystem components of the lakes/Rivers/Pacific Ocean under the combination of stressors scenarios.

On the basis of studied site [18], with differences in trophic status in according to the human intervention of associated sites, the IEM approach would be an interesting view point for understand limnological process. In example of multidisciplinary study is the first comparison between two north Patagonian lakes with differences within lake in trophic status due human intervention (Villarrica lake), in comparison with a few altered lake (Caburgua lake), it detected significant differences in trophic status, and plankton communities, that were related also with spectral properties [23], and probably it would be necessary more view points on the basis of basin management for understand the differences within a lake and between both lakes.

As conclusion, to satisfy future management needs, several indices must be developed based on the biological and water chemistry parameters and must be defined by legislation, describing the main biological indicators used for inland waters and coastal environment monitoring, to reveal positive aspects and weaknesses. As an answer to the failings of the existing tools, the possibility of using pelagic zooplankton as a new bioindicator in great lakes environments-Rivers which must be explored [38]. These organisms could represent an alternative solution since they possess many bioindicators criteria and are known in freshwater and coastal environments as highly sensitive to water quality changes [21,39], need an "Adaptive Management" based ecosystem approach completed with qualitative/quantitative analysis approach, within the Water Framework Directive (WFD) Framework to achieve a Good Environmental Status (GEnS) in the Chilean Great Lakes-Rivers basins especially those connected directly to the Pacific Ocean.

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