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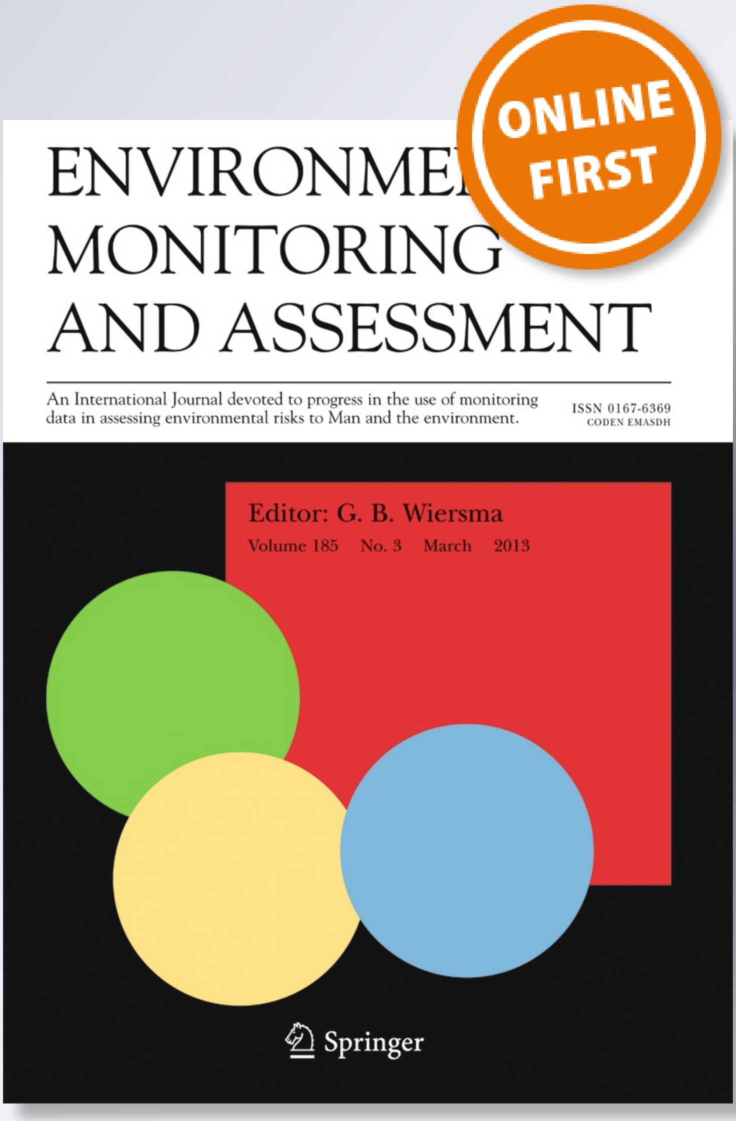

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Abstract The assessment of water vulnerability and pollution hazard traditionally places particular emphasis on the study on groundwaters more than on surface waters. Consequently, a GIS-based Lake Pollution Hazard Index (LPHI) was proposed for assessing and mapping the potential pollution hazard for shallow lakes due to the interaction between the Potential Pollutant Load and the Lake Vulnerability. It includes easily measurable and commonly used parameters: land cover, terrain slope and direction, and soil media. Three shallow lake ecosystems of the southeastern Pampa Plain (Argentina) were chosen to test the usefulness and applicability of this suggested index. Moreover, anthropogenic and natural medium influence on biophysical parameters in these three ecosystems was examined. The evaluation of the LPHI map shows for La Brava and Los Padres lakes the highest pollution hazard (≈30 % with high to very high category) while Nahuel Rucá Lake seems to be the less hazardous water body (just 9.33 % with high LPHI). The increase in LPHI value is attributed to a different loading of pollutants governed by land cover category and/or the exposure to high slopes and influence of slope direction. Dissolved oxygen and biochemical oxygen demand values indicate a moderately polluted and eutrophized condition of shallow lake waters, mainly related to moderate agricultural activities and/or cattle production. Obtained information by means of LPHI calculation result useful to perform a local diagnosis of the potential pollution hazard to a freshwater ecosystem in order to implement basic guidelines to improve lake sustainability.

Keywords GIS-based Lake Pollution Hazard Index · Shallow lakes · Land cover · Biophysical attributes · Pampa Plain (Argentina)

Introduction

Shallow lakes are integrated into the global water cycle and are, therefore, influenced by precipitation,

A. Romanelli · A. H. Escalante
Instituto de Investigaciones Marinas y Costeras (IIMyC),
Consejo Nacional de Investigaciones Científicas
y Técnicas (CONICET),
7600 Mar del Plata, Buenos Aires, Argentina

A. H. Escalante
e-mail: aescalan@mdp.edu.ar

A. Romanelli (✉) · H. E. Massone
Instituto de Geología de Costas y del Cuaternario,
FCEyN, Universidad Nacional de Mar del Plata,
Funes 3350, Nivel 1,
7600 Mar del Plata, Argentina
e-mail: aromanel@mdp.edu.ar

H. E. Massone
e-mail: hmassone@mdp.edu.ar

K. S. Esquius · A. H. Escalante
Laboratorio de Limnología, FCEyN,
Universidad Nacional de Mar del Plata,
Funes 3250, Nivel 2,
7600 Mar del Plata, Argentina

K. S. Esquius
e-mail: kesquius@mdp.edu.ar

evaporation, and water fluxes by groundwaters or surface waters. In addition to biotic and abiotic activities within these lakes, organic matter, nutrients, and elements from the surroundings are transferred via the water flow into the system (Burkert et al. 2004). More generally, chemical composition in water bodies is the outcome of lithological, climatic, biological or human factors, and of geochemical processes interacting in the aquifers and across the catchments (Fernández Aláez et al. 2006).

Given that wetlands are linked through the hydrological system to upstream and downstream areas, that happening upstream will affect them while that happening in the wetland will affect the environment and people living downstream (Price and Maloney 1994). Several studies have shown that land use has a strong influence upon water chemistry and aquatic biota (Ometo et al. 2000; Collier and Quinn 2003; Shivoga et al. 2007). Since water resource systems are subject to different anthropogenic pollution impacts, the conduction of studies on water vulnerability is helpful to further know the nature of water resource system and thus to utilize and protect them more effectively, promoting their sustainable development. The most logical approach to the definition and assessments of water vulnerability and pollution hazard traditionally places particular emphasis on the study on groundwaters (Margat 1968; Aller et al. 1987; Vrba and Zaporozec 1994; Massone et al. 2010), and there are less studies on surface waters (Eimers et al. 2000; New Mexico Environment Department 2000; Harum et al. 2004; Yanhui et al. 2012). Vulnerability has been used several times with the meaning of risk, but the authors prefer to use the term vulnerability for the situation in which it only represents the intrinsic characteristics of the natural medium, determining the likelihood of this medium to be adversely affected by an imposed contaminant load. As a general definition, pollution hazard could be defined as the interaction between the pollutant loads applied on the environment (as a result of human activity) and the vulnerability of the physical medium consequent upon its natural characteristics (Foster et al. 2002).

Watershed management and catchment scale studies have become increasingly important for determining the impact of human activity on water quality, both within the watershed and in receiving waters. Effective analytical tools, such as Geographical Information Systems (GIS), high-resolution digital land-use data and multivariate statistics, are able to deal with spatial data and complex interactions and are entering into common usage in watershed management. Although there have been some studies on the impacts of land use on water quality, the complex intrinsic relationships between land use and water quality are yet to be elucidated (Bahar et al. 2008).

The Pampa Plain in Argentina is one of the most extended plain regions of the world. Climate, as well as its geomorphology, results in the development of wetland systems and very shallow lakes (Iriondo 1989), which play an important role in the overall hydrological cycle of Buenos Aires Province (southern Pampa) (Fernández Cirelli and Miretzky 2004). They contribute to the equilibrium of physical and biological systems among several ecosystem services (i.e., nutrient cycling, water and climate regulation, recreation). Intensive human use (mainly agriculture activities and urbanization) of these ecosystems leads to an equilibrium disruption on them, becoming highly vulnerable systems. Although it is well-known that these shallow lakes undergo environmental stress (Quirós and Drago 1999; Quirós et al. 2002a), at present less is known about the relationship between lake conditions and land use in this region.

The aim of the present study is to generate a GIS-based Lake Pollution Hazard Index (LPHI) for assessing and mapping the potential pollution hazard to shallow lakes due to the interaction between the Potential Pollutant Load (PPL) and the Lake Vulnerability (LV) to pollution according to the natural medium features of its surrounding land. Moreover, anthropogenic and natural medium influence on biophysical parameters in lake ecosystems was examined.

The term vulnerability here is considered in a broader sense since it is hard to interpret lake condition without reference to its surrounding land which constantly functions as a supplier of various forms of material including that introduced directly or indirectly by man. The GIS-based Lake Pollution Hazard Index is an exploratory assessment tool to evaluate the potential impact of human activities, associated to the different land uses in the area, in relation to the ecosystem susceptibility to pollution. As a result, it constitutes a valuable decision-making tool for optimizing the management of water resources and land-use planning. Three shallow lake ecosystems were chosen to test the usefulness and applicability of this suggested index and proposed assessment framework.

These systems are representative freshwater environments of the southeastern Pampa Plain in Argentina, each one with different land use, soil, and topographic characteristics and also management regulations for natural resource protection.

Problem-in-context

Three shallow polymictic and permanent lakes located in the southeastern Pampa Plain were selected for this study: La Brava, Los Padres, and Nahuel Rucá lakes, belonging to Balcarce, Mar del Plata and Mar Chiquita districts, respectively (Fig. 1; Table 1). Moreover, these inland water bodies are included in the Mar Chiquita Coastal Lagoon Basin (10,000 km^2). The first two ecosystems are surrounded by the Tandilia Ranges, a block-mountain system with a maximum elevation of 250 m above sea level, and belong to an intermountain environment. Contrary, Nahuel Rucá Lake is located in a plain environment.

Each water body has only one inflow stream (El Peligro, Los Padres and Dulce streams, respectively) which is born in the ranges and flow through agricultural lands before discharging to the shallow lake, and an outflow one (Tajamar, La Tapera and Sotelo streams, respectively). La Brava, Los Padres, and Nahuel Rucá lakes have abundant organic matter and high nutrient concentrations which determine their high eutrophication level since their origin (Quirós and Drago 1999).

La Brava, Los Padres, and Nahuel Rucá lakes are immersed in crop–livestock agroecosystems, and except for the latter, they are considered important places for recreation and nature education. Nahuel Rucá Lake is included in a private farmland for cattle breeding, so little access to the water body is possible. In the northern sector of La Brava Lake, a residential zone (La Brava Village) has been developed, with important permanent population growth over the last years (300 residents). In addition, close to Los Padres Lake there is a residential neighborhood (Los Padres Village) with a thousand families. The main disturbance in the last two ecosystems occurs during weekends and holidays when large numbers of people use these areas for recreational activities. Several tourism-related enterprises are also located along their basins. Like most of the shallow lakes of the Pampa Plain, these water bodies have also a fundamental role in the conservation of biodiversity by providing habitat for resident and transient species, allowing their survival, feeding and reproduction (Josens et al. 2009).

The expansion of agricultural activity in the region, technology, urbanization, and the waste increase from different origins, among others, may generate a negative impact on water quality, in detriment of current and potential uses. The acceleration of the eutrophication process threatens the conservation of such environments (Grosman 2008). Several studies confirm the anthropogenic impacts on the ecosystems under study, showing the presence of diverse pollutants (heavy metals, pesticides, and herbicides) in water, soil, aquatic macrophytes, and fauna (Miglioranza et al. 1998, 2004; Massone 2011; Ondarza et al. 2012).

Regarding the managing figures of these natural resources, at the moment, a proposal to declare La Brava Lake Basin as a “Protected Landscape of Provincial Interest” (law no. 12704) is being evaluated by the Buenos Aires Provincial Agency for Sustainable Development. This project focuses on ensuring the conservation of this freshwater ecosystem and its surroundings by developing a system of a wetland basin protected area, which adopts an integral approach for water resource management. A territorial ordination plan in the area has not yet been applied. In the case of Los Padres Lake, since 1982 an area of 6.87 km^2 has been declared a Natural Reserve. It is a natural area for the preservation of the flora, fauna, and the water body. A managing plan was developed, including three different zones: intangible (0.9 km^2), conservation, and multiple-purpose zones. However, people normally use the coast in a chaotic way, occasionally grouping together for fishing, picnicking, and playing soccer (Cardoni et al. 2008), and also covert activities are conducted. Finally, Nahuel Rucá Lake has neither a managing plan nor tourism or recreational activities on it.

With respect to the ownership status, they are complex natural ecosystems. Although water itself is part of the public domain (Ministry of Agricultural Affairs of the Province of Buenos Aires), several ownerships are involved. In La Brava Lake, the provincial and municipal governments, two tourism-related enterprises, the inhabitants of La Brava Village and the landowners (who own most of the shore of the lake) are implicated. In the area of Los Padres Lake, the provincial and municipal governments are the

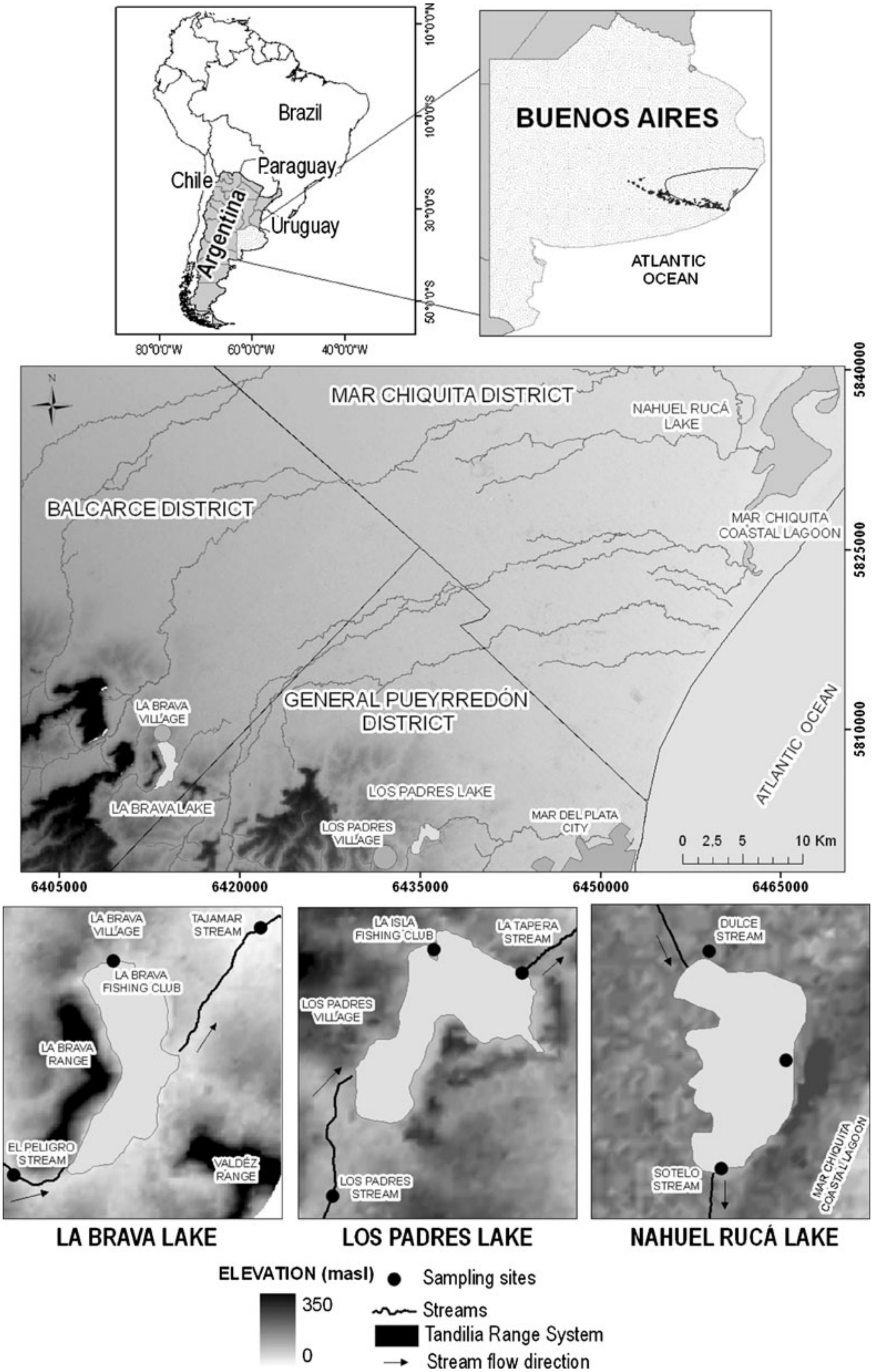

Fig. 1 Location map and sampling sites

Table 1 Main environmental characteristics of La Brava, Los Padres, and Nahuel Rucá lakes

	La Brava	Los Padres	Nahuel Rucá
Altitude (m above sea level)	71.62	53.18	3.19
Slope (degrees)	4.04	2.71	1.24
Geomorphological environment	Intermountain	Intermountain	Plain
Area (km^2)	4	2.16	2.71
Maximum depth (m)	4	2.1	0.16
Water type	Na-HCO$_3$	Na-HCO$_3$	Na-HCO$_3$-Cl
Trophic state	Eutrophic	Eutrophic	Eutrophic
Aquatic macrophytes	Marshy and free- floating species	Marshy and free- floating species	Marshy, submerged and free-floating species
Gate for hydrometric level regulation	No	Yes (outflow stream)	Yes (outflow stream)
Lake–aquifer relationship	Effluent–influent	Effluent–influent	Possibly effluent–influent
Constructed area along the shoreline (%)	2.2	6.57	0

proprietaries. However, there are different tourism enterprises located in the coastline, which have some autonomy for decisions and control, and depend on the local government. In the case of Nahuel Rucá Lake, although the water body belongs to the provincial administration, it is part of a private farmland that controls the access to the lake.

Materials and methods

Estimation of the GIS-based Lake Pollution Hazard Index

A GIS-based LPHI for shallow lake ecosystems was calculated combining (1) the PPL and (2) LV, according to the natural medium features of its surrounding land. The first factor was obtained from land cover information, considering that each different land cover could be associated to specific potential pollutant loads. In this sense, the PPL map represents land cover categories that store, use or produce, as a product or by-product, any contaminant. The combination of topographic (terrain slope and direction) and soil data, as relevant factors in water and/or pollutant drainage due to surface runoff into shallow lakes and streams, generates the second factor mentioned above. The applied methodological framework for shallow lake pollution hazard assessment is synthesized in Fig. 2.

The PPL assessment for each shallow lake ecosystem was performed on the basis of the land cover map. The weight of each land cover type is a value given by us based on one criterion: the potential effect of land use upon surface water quality with regard to the associated potential pollutant loads (Table 2). Moreover, each subcategory within a land cover type also received a 1–5 rating. In this sense, the most potentially dangerous ones are given a rating of 5, whilst the least ones receive a rating of 1. The water body land cover type was masked off in order to avoid it in the analysis. Land cover categories were generated on the basis of satellite images of Landsat TM and field trips, within a buffer zone of 2.5-km radius from each shallow lake (analysis unit) which includes the most representative human activities and natural medium features of the environment next to these water bodies, following the CORINE Land Cover (CLC) nomenclature (European Environmental Agency 2000). The minimum cartographic unit was 1 ha and the level 3 CLC nomenclature was used. Each land cover type was digitized on screen as polygon coverages by using the GIS software ArcGis 9.2 (ESRI 2007). PPL is calculated from the equation below:

$$\mathrm{PPL} = \mathrm{LC}_{\mathrm{wi}} \times \mathrm{LC}_{\mathrm{ris}} \qquad (1)$$

where PPL is the Potential Pollutant Load for a mapping unit; w is the weight factor for each land cover type (LC_{i}), and r is the rating for each land cover type subcategory ($\mathrm{LC}_{\mathrm{is}}$).

LV was estimated combining three parameters: terrain slope (TS), slope direction (SD), and soil media (SM). Slope is a critical parameter with a direct control on runoff and therefore on infiltration (Ravi Shankar and Mohan 2006). The worst conditions for lake pollution

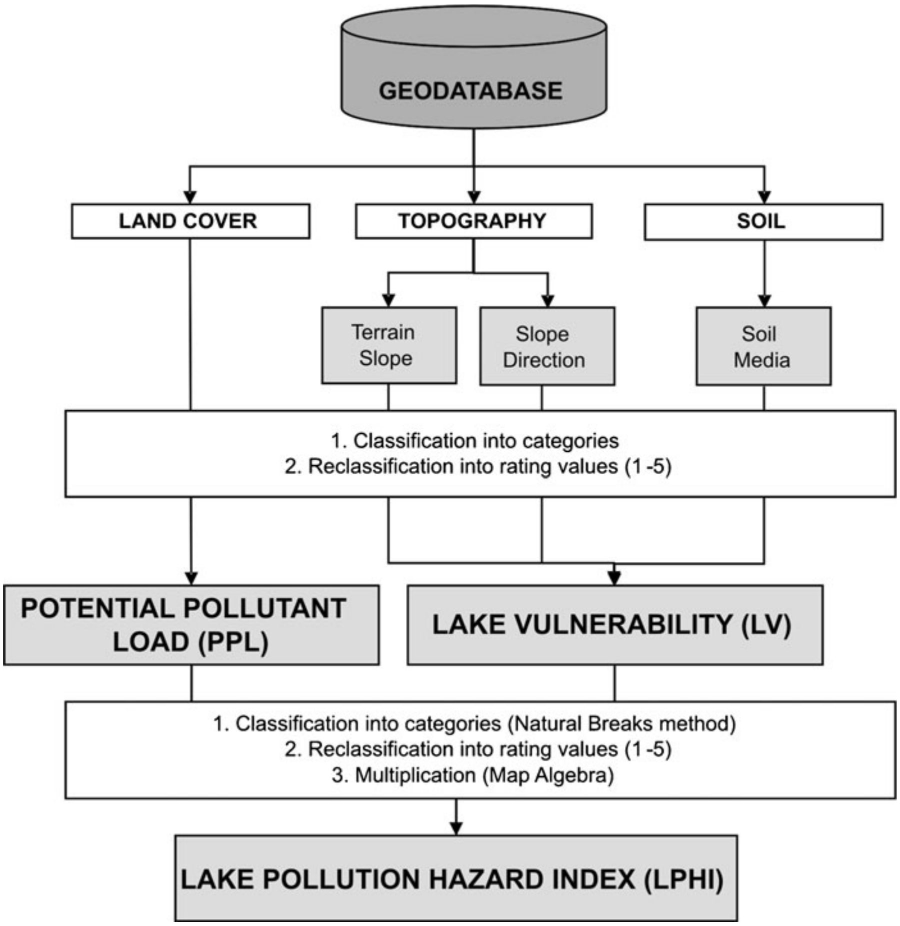

Fig. 2 Methodological framework for estimating the PPL, the LV, and the LPHI maps

hazard usually occur in high topographic areas, facilitating water movement and surface runoff to the water bodies. Aspect can be thought of as the slope direction, and it identifies the downslope direction of the maximum rate of change in value form each cell to its neighbors. The values of the output raster are the compass direction of the aspect (0° to 360°, where 0° and 180° correspond to the N and S direction, respectively). Soil has a significant impact on the amount of infiltration into the ground and hence on the ability of a contaminant to move vertically into the vadose zone (Aller et al. 1987). The infiltration capacity depends on the type of the soil, sandy loam soil having more infiltration capacity than clay loam soil because of the high porosity and permeability of the first soil type (Bennett 2001). Low permeable soils (silt–clay to clay soils) facilitate surface runoff, being the worst condition for lake pollution hazard.

TS and SD were generated from a Digital Elevation Model of the Shuttle Radar Topography Mission of NASA. Then the slopes were classified into four groups according to the mean, 25th and 75th percentile slope values (Table 3). Regarding SD, the 2.5-km buffer zone from each shallow lake was divided into four quadrants, and the main directions of surface runoff to the water bodies received a rating of 5 while the noninfluential ones received a rating of 1. The dominant slope direction per quadrant was selected based on the conceptual model of each ecosystem local flow. Although ratings for each parameter categories have been given in this version of the index, it is imperative that each user establishes their values for each parameter according to the features of a specific study area. Soil media (SM) was obtained from soil texture data provided by INTA (2008). In order to obtain the LV, a multiplication of the reclassified maps (TS, SD, and SM) is performed, by the application of map algebra. Lake Vulnerability can be obtained from the equation below:

$$LV = TS_r \times SD_r \times SM_r \tag{2}$$

Table 2 Weights and rating values for each land cover type (CORINE Land Cover, level 3)

Land use	Land cover type level 3 (LC_i)	Weight	Subcategory (LC_{is})	Rating
Nature conservation	Coastal lagoon	2	Salt water discharge into the lake	5
			Probable salt water discharge into the lake	3
			No salt water discharge into the lake	2
	Bare rock	1	Ranges far away from the lake	3
			Presence of ranges close to the lake (<0.5 km)	1
	Broad-leaved forest	1	<5 %[a]	5
			≥5 % to <10 %[a]	4
			≥10 % to <20 %[a]	3
			≥20 % to <30 %[a]	2
			≥30 %[a]	1
	Natural grassland	1	<10 %[a]	5
			≥10 % to <30 %[a]	4
			≥30 % to <60 %[a]	3
			≥60 % to <80 %[a]	2
			≥80 %[a]	1
Recreational	Sport and leisure facilities	3	Motorized activity allowed on water	5
			Non-motorized activity allowed on water	4
			Vehicle access	3
			No vehicle access	2
			No recreational access	1
Residential	Discontinuous urban fabric (low-intensity residential use)	5	Public wastewater effluent introduced into lake area and private septic system present	5
			Private septic system present	4
			No wastewater discharges present	1
Agricultural	Pastures	4	Presence of heavy grazing activities	5
			Presence of minimal grazing activities	3
			No cattle presence	1
	Non-irrigated arable land	5	≥75 % of total agricultural land	5
			≥50 % to <75 % of total agricultural land	4
			≥25 % to <50 % of total agricultural land	3
			≥10 % to <25 % of total agricultural land	2
			<10 % of total agricultural land	1
	Permanently irrigated land	5	≥75 % of total agricultural land	5
			≥50 % to <75 % of total agricultural land	4
			≥25 % to <50 % of total agricultural land	3
			≥10 % to <25 % of total agricultural land	2
			<10 % of total agricultural land	1

[a] Percentage of the 2.5-km shallow lake buffer zone

where LV is the Lake Vulnerability for a mapping unit and r is the rating for each parameter: terrain slope (TS), slope direction (SD) and soil media (SM).

Several thematic maps necessary for the PPL, LV and, finally, the LPHI were prepared on the basis of four parameters (LC, TS, SD, and SM) by using the GIS software ArcGis 9.2. After the preparation of these maps for each shallow lake ecosystem under consideration, they were transformed into raster format (using the spatial analysis module of ArcGIS). A

Table 3 Rating values for each parameter necessary to estimate LV

Parameter	Category	Rating
Terrain slope	≥75th percentile (degrees)	5
	>Media to 75th percentile (degrees)	4
	>25th percentile to ≤ media (degrees)	3
	≤25th percentile (degrees)	1
Slope direction	Slope direction favors surface runoff to the water bodies	5
	Slope direction does not favor surface runoff to the water bodies	1
Soil media	Clay–silt clay (low permeable soils)	5
	Silt–silt loam (moderate permeable soils)	3
	Sand loam–loam (high permeable soils)	1

spatial cell resolution of 30×30 m was used. All GIS information was projected in the Gauss Krüger system, zone 6 (Campo Inchauspe).

The classification of each thematic map involved subdividing the information into several categories to enable the mapping of the PPL, LV, and LPHI. In this sense, each thematic map was reclassified into rating values according to the range of each category: 1, very low; 2, low; 3, moderate; 4, high and 5, very high. Here, a value of 5 would indicate an area with conditions that favor the highest potential for lake pollution hazard while a value of 1 would indicate the opposite situation.

In order to enable zonation of lake potential pollution hazard, the LPHI is obtained by multiplying the PPL and LV maps by the application of map algebra. The final index can be computed using the following formula:

$$\mathrm{LPHI} = \mathrm{PPL}_\mathrm{r} \times \mathrm{LV}_\mathrm{r} \qquad (3)$$

where LPHI is the Lake Pollution Hazard Index for a mapping unit and r is the rating for each factor: PPL and LV.

Reclassification of the PPL, LV, and LPHI maps according to the Natural Breaks (Jenks) method (provided by ArcGIS 9.2), which recognizes five classes from 1 (lower values in the series) to 5 (higher values), was done in order to obtain each category. In this reclassification, classes are based on natural groupings in the data distribution. This method identifies breakpoints between classes using a statistical formula called Jenks' optimization (Jenks and Caspall 1971; Jenks 1977). It is rather complex, but basically it minimizes the sum of the variance within each class (Slocum 1999; Murray and Shyy 2000).

Anthropogenic influence on biophysical parameters

In order to examine the effects of human activities and natural characteristics on surface water chemical composition and some of their biological communities (periphyton and phytoplankton), three sampling sites were selected in each shallow lake ecosystem: La Brava, Los Padres, and Nahuel Rucá lakes (Fig. 1). One representative sample from the shallow lake and its related streams (inflow and outflow) was seasonally collected from May 2009 to June 2010. These sampling sites have abundant marshy macrophyte (*Schoenoplectus californicus*) and are easy to access from the shoreline. Since the sampling period coincided with the driest months of the last 10 years, some sites occasionally could not be sampled.

Water samples (1,000 mL each) were obtained at each sampling site. The collection, preservation, and chemical analysis for major ions of water samples were made following the standard methods given by the American Public Health Association (APHA 1998). Chemical analyses were: dissolved oxygen by Winkler method with azide modification, biochemical oxygen demand (BOD, 5 days, 20 °C), NO_3^- by the Brucine method, total dissolved phosphorus (TDP) by ascorbic acid method and turbidity by an Orbeco-Hellige turbidimeter. Hydrochemical analyses were carried out at the Laboratorio de Hidrogeoquímica e Hidrología Isotópica (Universidad Nacional de Mar del Plata). Water temperature, transparency (Secchi disk), and depth were in situ-estimated. The depth/photic depth relationship ($Z_\mathrm{d}/Z_\mathrm{p}$) was calculated using depth measurements and Secchi disk lectures for each sampling site (Quirós et al. 2002a).

For periphyton analysis, 20 stems of *S. californicus* (20-cm long, cut beginning at the water surface) were randomly removed up every season from each station along a transect parallel to the shoreline. Ten samples were used to evaluate periphytic chlorophyll *a* (Chl*a*) concentration, and the same number of stems was used to estimate dry weight (DW), ash (AS), and ash-free dry weight (AFDW) contents. Chlorophyll *a* concentration was measured by spectrophotometry and was calculated using equations given by Cabrera Silva (1983). For DW analysis, periphyton was pre-weighted and dried at 105 °C until constant weight. For AS determination, dried samples with retained material were combusted at 505 °C and re-weighted. AFDW content was calculated as the rest of DW and AS. We expressed Chl*a*, DW, and AFDW as microgram (for Chl*a*) or milligram (for DW and AFDW) per square centimeter, considering the bulrush area as the lateral area of a cylinder (Esquius and Escalante 2012). These biological parameters were used to calculate Lakatos indices (Lakatos et al. 1999), which have been successfully applied in lotic and lentic environments of South America (Pizarro and Alemanni 2005; Leandrini and Rodrigues 2008) and allow inferring about the functionality of the periphyton community.

Finally, for the phytoplankton analysis, water samples were also collected in each sampling site to estimate chlorophyll *a* concentration. Pigment concentration was estimated using equations given by Jeffrey et al. (1997).

Results and discussion

Land cover and potential pollutant load analysis

Land cover was classified into 10 distinct categories: non-irrigated and permanently irrigated lands, broad-leaved forest, water body and coastal lagoon, pastures, natural grassland, bare rock, sport and leisure facilities, and discontinuous urban fabric (Table 4). The three shallow lake ecosystems under consideration have dissimilar land covers (Fig. 3). Non-irrigated arable land covered 63.65 % of the total 2.5-km-radius buffer zone of La Brava Lake, being 27.25 % and 5.22 % in Nahuel Rucá and Los Padres lakes, respectively. Regarding Los Padres Lake, permanently irrigated land occupied the largest area (63.88 %), not present in the other ecosystems. On the other hand, pastures were the main land cover in Nahuel Rucá Lake (44.15 %) while in the other sites this category was less than 5.00 %.

Artificial surfaces, like sports and leisure facilities, and discontinuous urban fabric were only identified in Los Padres and La Brava lakes. The area occupied by the first land cover type was similar in both ecosystems (≈1.45 %), whereas the discontinuous urban fabric was 1.5 times higher in Los Padres Lake (5.81 %). However, the residential village is much closer to La Brava Lake than Los Padres. One special feature is the presence of bare rock category in La Brava Lake and the coastal lagoon in Nahuel Rucá Lake.

Intermountain environments has >65 % of areas with high to very high potential pollutant load (73.39 % and 68.19 % in La Brava and Los Padres lakes, respectively) (Fig. 4a, b). Agricultural activities in these ecosystems, which involved the use of great amounts of fertilizer (Miglioranza et al. 2004), together with residential/urban land cover, were considered as high-pollution potential sources. Despite this, discontinuous urban fabric actually appeared as a low significant land cover in La Brava and Los Padres lakes; the continuous demographic expansion of Balcarce and Mar del Plata cities could negatively impact these ecosystems in the near future. In Nahuel Rucá Lake, pasture (sometimes with livestock) constituted the predominant land cover, followed by non-irrigated arable land being sources with moderate potential of pollution to the lake (Fig. 4c). On the contrary, it does not have areas with high and very high PPL. The absence of urban development and scarce good agricultural soils around this ecosystem (Maceira et al. 2005) a priori suggests that the PPL related to these land covers would not necessarily increase in the future. Nevertheless, El Dulce Stream is a direct source of pollutants and/or solids in suspension because it flows through an extensive and productive area before discharging into the shallow lake (Lima et al. 2011).

Knowledge of the present distribution and area of such agricultural, recreational, and urban lands is needed by legislators, planners, and state as well as local governmental officials to determine better land use policies to identify future development pressure points and areas and to implement effective plans for regional development. Land use and land cover data are also needed for water resource inventory, deteriorating environmental quality, destruction of important wetlands, water supply planning, and protection of

Table 4 Brief description of each land cover type (according to Corine Land Cover, Level 3) in the three shallow lake ecosystems

Land cover type (level 3)	Description
Water body	It includes La Brava, Los Padres, and Nahuel Rucá shallow lakes. Their littoral zone is mainly dominated by *S. californicus*, with greater development in the inflow and outflow areas. This vegetation plays a key role since it acts as a barrier between land and the water system (Joniak et.al 2007).
Coastal lagoon	It corresponds to Mar Chiquita Coastal Lagoon, which has been declared as a "Biosphere Reserve" by the UNESCO. This lagoon constitutes an estuarine environment with an area of 60 km^2 and a tributary basin of 10,000 km^2. It has a very important input of inland water through streams and channels coming from the Tandilia system, where very important farming activity is developed (Beltrame et al. 2008). Vegetation is characterized by a halophytic community (Stutz and Prieto 2003).
Bare rock	The Tandilia Hills is the unique semi-pristine area. It contains forest and shrubs, and the only two autochthonous plant species (*Colletia paradoxa* and *Celtis tala*).
Broad – leaved forest	Land under natural or planted stands of trees. The exotic tree species within the area are *Ulmus pumila*, *Pinus* spp. and *Cupressus* spp.
Natural grassland	Small isolated fragments which could have some human intervention. Grasses of the genera *Stipa*, *Bromus*, *Paspalum*, and *Sporobolus* predominate in this sector of Buenos Aires Province (Jarrige and Béranger 1992).
Sport and leisure facilities	An area that offers you camping, fishing, boating, picnicking, parking of motor homes and other outdoor fun is administrated by the tourism entrepreneurs. These small tourist entrepreneurs are located along the wetland shores and also near their basins. In most of them, the septic system is unavailable.
Pastures	Land permanently used for herbaceous forage crops. Pastures are a mixture of legumes and grasses. Fertilizers could be used in some periods of the year. Nahuel Rucá Lake is an area for breeding cattle.
Non-irrigated arable land	The main crops are soybean, zea may, wheat, and sunflower. Their growth in the area requires the application of fertilizers and pesticides. Farming methods have modernized and intensified over the years directed towards increasing commercial production.
Permanently irrigated land	Crops cultivated with an artificial water supply developed in small plots of land (specially dedicated to the production of vegetables, strawberries, kiwi, and ornamental plants). It includes the Horticultural Belt of Mar del Plata City, where manure application and irrigation are extensively used for maintaining the high productivity of horticultural plants, leading to contamination problems in the water supply sources (Baccaro et al. 2006).
Discontinuous urban fabric	It includes two important residential villages, La Brava and Sierra de Los Padres, located close to La Brava and Los Padres lakes, respectively. Septic system is unavailable. Due to the scenic attractions and the quietness of these places, an increasing permanent population from Mar del Plata and Balcarce cities is evident during the last years.

zones identified as recharge areas for the aquifer (Anderson et al. 1976). Thus, the land cover map for each shallow lake ecosystem was produced in order to show the distribution of the different activities performed in this zone and also to associate it with a potential pollutant load.

Lake vulnerability assessment

High lake vulnerability (LV) zones are mainly associated to moderate–high slopes (>2°, which favor surface runoff to the water body) and moderate permeable soils (loam–silt texture). On the contrary, areas with low vulnerability are related to low terrain slopes (<2°, which do not favor water movement and transfer of solid particles and pollutants) and low to moderate permeable soils (loam–sand and loam–silt textures).

In the La Brava ecosystem, areas with high to very high LV (22.02 %) coincide with the stream and groundwater recharge area to the shallow lake and the urban settlement (Fig. 4d). On the other hand, very low to low LV zones (53.53 %) are located 1.5 km far away the shallow lake in the NE and W sector of the 2.5-km buffer area. The Los Padres Lake ecosystem shows an opposite pattern with low to very low categories located close to the shallow lake and in a dispersed manner

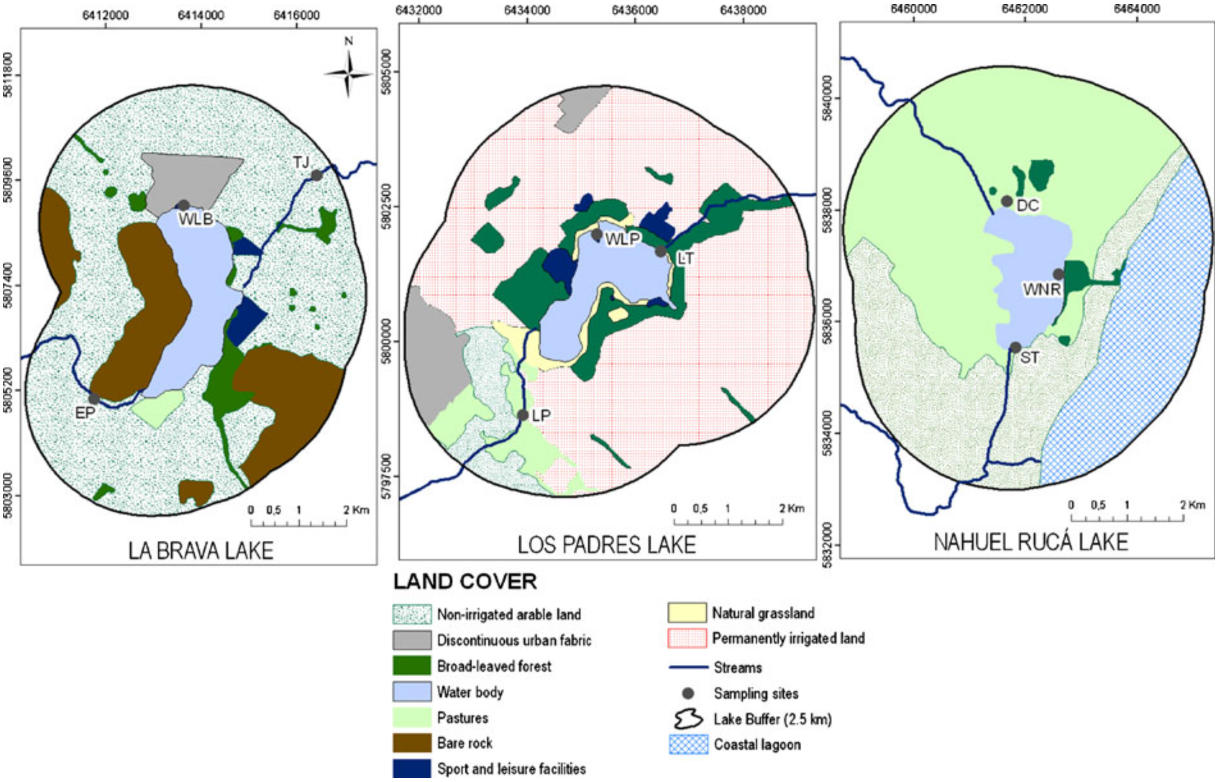

Fig. 3 Land covers maps in **a** La Brava, **b** Los Padres, and **c** Nahuel Rucá lake ecosystems. El Peligro Stream (*EP*), La Brava shallow lake (*WLB*), Tajamar Stream (*TJ*), Los Padres Stream (LP), Los Padres shallow lake (*WLP*), La Tapera Stream (*LT*), Dulce Stream (*DC*), Nahuel Rucá shallow lake (WNR), Sotelo Stream (*ST*)

(46.85 %) (Fig. 4e). The W and SW sectors have the highest LV with high to very high ratings (30.11 %). Even though the Nahuel Rucá Lake ecosystem has the lowest area percentage with high LV (20.66 %), these sites are mainly located in the stream and groundwater recharge zone to the water body (Fig. 4f). Finally, approximately 60 % of the area has low to very low LV.

GIS-based Lake Pollution Hazard Index estimation

An integrated analysis of land cover, terrain slope, slope direction, and soil media allowed identifying areas with different potential pollutant hazard for surface water. Figure 5 shows the resulting maps obtained by applying the LPHI in three shallow lake ecosystems of the southeastern Pampa Plain. The description of each LPHI category is as follows (Table 5):

1. This site has a *very low* potential pollution hazard to surface water. No damaging effects due to the apparently absent potential sources of pollution to shallow lakes and streams and/or good natural conditions, which do not favor surface runoff to water bodies. This is not a priority area for water and soil resource management.
2. This site has a *low* potential pollution hazard to surface water. Presence of sources with low potential of pollution to shallow lakes and streams. If land use practices are maintained at current level, the probability of an adverse impact to water resources would be low.
3. This site has a *moderate* potential pollution hazard to surface water. Sources with moderate potential of pollution to surface waters. The probability of an adverse impact to water resources is greater than that from a low-rated site. Some remedial action should be taken to lessen the probability of pollution problems.
4. This site has a *high* potential pollution hazard to surface water. There is a high probability of an adverse impact to water resources unless remedial action is taken. Soil and water conservation as

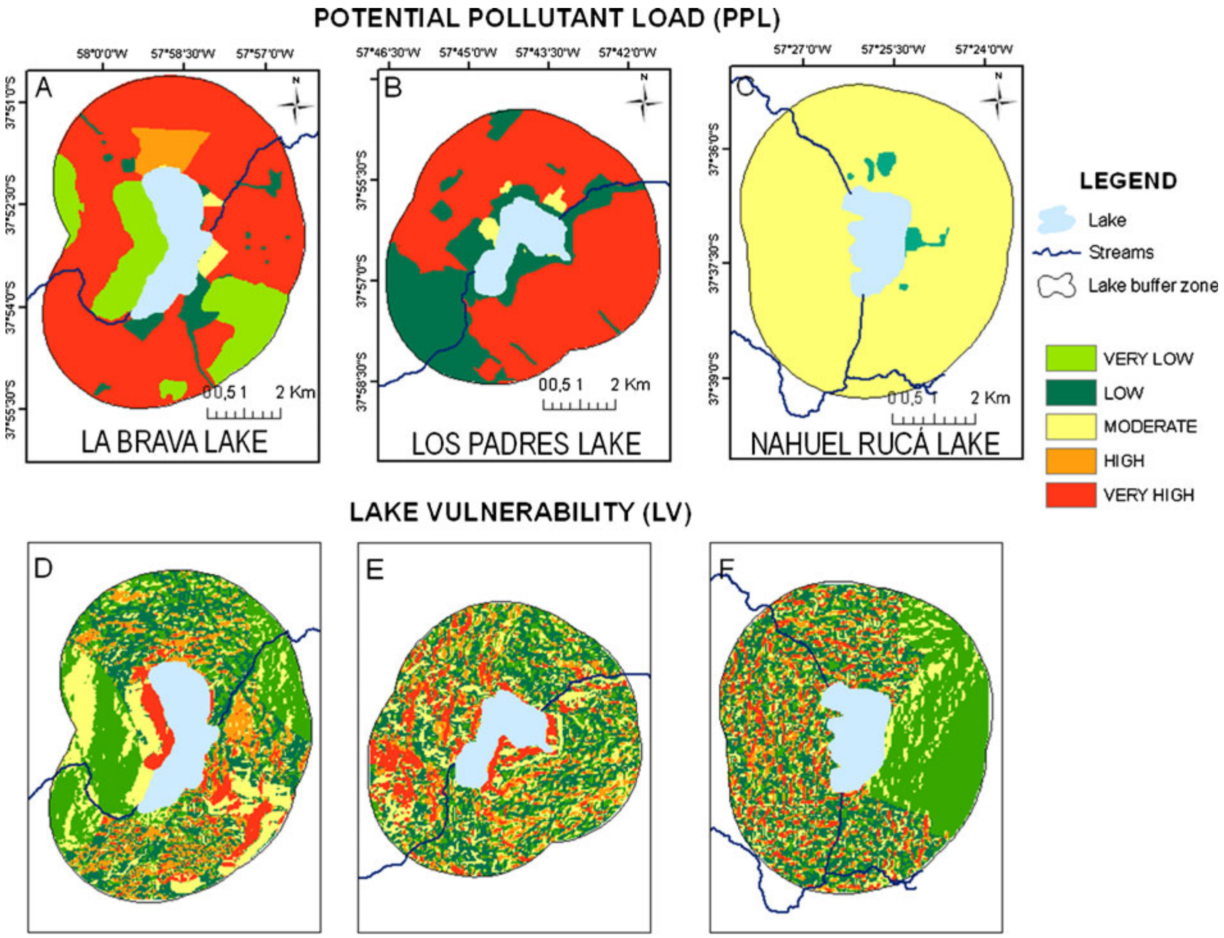

Fig. 4 PPL and LV maps for **a** La Brava, **b** Los Padres, and **c** Nahuel Rucá lake ecosystems

well as prevention practices are necessary to reduce the risk of lake pollution with probable water quality degradation.

5. This site has a *very high* potential pollution hazard to surface water. The probability of an adverse impact to water resources is very high due to the presence of sources with high potential of pollution to shallow lakes and streams. They contribute with high quantities of sediment, nutrients, and other pollutants to the water systems. Remedial measures should be initiated to reduce the risk of pollution. This is a priority area which requires the implementation of recommended management practices.

The evaluation of the LPHI map suggests that the intermountain ecosystems hold the highest pollution hazard (≈30 % with high to very high category). Due to the predominance of >2° slopes and urban land close to La Brava Lake, water pollution from liquid and solid waste disposal could be increased. Besides, the existence of agricultural land use in the recharge areas coinciding with topographic high zones is particularly important to protect because misuse of these areas can lead to depletion of potable water supplies downstream and increased lake contamination. Even if the Los Padres Lake shows a similar LPHI value to the La Brava Lake, probably the presence of land cover categories associated to low potential pollution load surrounding the shallow lake (broad-leaved forest and natural grassland) could favor water runoff retention and the possible contribution of upstream pollutants.

Regarding the Nahuel Rucá Lake, it seems to be the less hazardous water body (just 9.33 % with high LPHI) because it is associated to the lowest slope values (<0.98°) and land covers with moderate

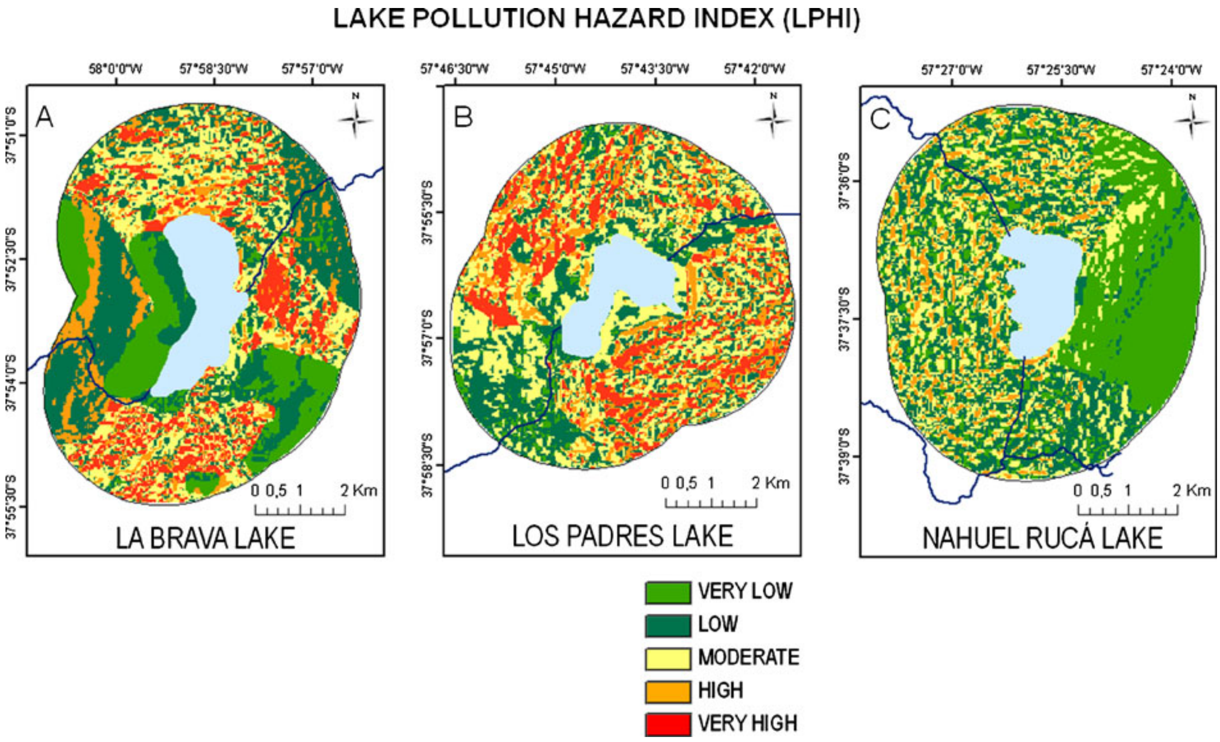

Fig. 5 LPHI maps for each shallow lake ecosystem: **a** La Brava, **b** Los Padres, and **c** Nahuel Rucá lakes

pollution load. However, it is important to notice that its inflow stream flows 102 km through crop–livestock lands before discharging to the lake allowing that sediment particles and/or agrochemicals from upstream land use could reach the water body (Ondarza et al. 2012).

An advantage of the GIS-based LPHI is that authorities can rank the potential pollutants of watersheds, identify critical contributing areas, and initiate control strategies to target source pollution of high priority watersheds. Moreover, the utility of this index for predicting and providing information about sitting vulnerable areas in a lake management process is applicable to different time and space scales. In this sense, if the land cover category of an area change, for example, from forestland to residential, the environmental impact of the land use change could be assessed by considering the change in the LPHI value.

The increase in LPHI value is attributed to a different loading of pollutants governed by land cover category and/or by the exposure to high slopes and influence of slope direction. Land use is recognized to be the main cause of nonpoint source pollution in a watershed. This LPHI value can be modified, increased or decreased, when applied to a specific land use scenario, resulting in a different pollution potential load attributed to the change in land cover category. Practically, there are no limitations of applying this GIS-based index in the assessment of potential pollution hazard to surface water in a specific area since it includes easily measurable and commonly used parameters (obtained from satellite images and topographic data) which can be spatially and temporarily analyzed. Moreover, it allows the updating of information and the addition of several available maps with relative ease (e.g., crop types, agrochemical determinations in groundwater, and surface water) to improve landscape evaluations.

Table 5 Classes and categories of PPL, LV, and LPHI

Category	PPL Classes	LV	LPHI
Very high	>20	>45	>16 to ≤25
High	>15 to ≤20	>25 to ≤45	>12 to ≤16
Moderate	>5 to ≤15	>12 to ≤25	>6 to ≤12
Low	>1 to ≤5	>5 to ≤12	>3 to ≤6
Very low	1	≤5	≤3

It can be rightly argued that the proposed index represents an oversimplification of a complex reality; however, it provides useful representations of reality, often highlighting significant features that may not be so obvious in a photograph. As any index intended to support management decisions, the LPHI requires both verification and validation because all models are necessarily simplifications of reality. The present index has, in fact, been substantially verified in the sense that it adequately represents the natural and human conditions of the basin based on our own field analysis.

Anthropogenic influence on biophysical parameters

In order to perform an effective and integrated study of surface water susceptibility to pollution, chemical and biological attributes must be taken under consideration besides the spatial analysis of land use and natural ecosystem features. In this sense, anthropogenic and natural medium influence on biophysical parameters in three shallow lake ecosystems was examined.

Related to nutrient concentration, mean NO_3^- and TDP values were similar in the intermountain lakes and quite higher in Nahuel Rucá Lake (Fig. 6a, b). In spite of the moderate potential pollution hazard of the latter, the direct contribution of livestock excreta to NO_3^- and TDP input to the shallow lake could explain the nutrient concentration increase. Regarding Los Padres and La Brava lakes, even though they have high potential inputs of these nutrients linked to non-point (agricultural activities through fertilizer application) and point source pollution (sports–leisure facilities and discontinuous urban fabric close to them through domestic effluents), and high vulnerability (according to the natural medium features), low values were detected. In Los Padres Lake, the presence of forest and natural grassland surrounding the shallow lake could favor water runoff retention and the possible contribution of upstream pollutants while in La Brava Lake, the dilution effect of nutrient concentration due to the lake volume (in general, three times higher than in Los Padres Lake) could explain the lower values here detected.

Dissolved oxygen (DO) and BOD_5 values were similar in these three ecosystems and indicated a moderately polluted and eutrophicated condition of their waters mainly related to moderate agricultural activities and/or cattle production (Gómez and Licursi 2001) (Fig. 6c, d). Similarly, during all the study period, the three shallow lakes were in a turbid phase with scarce Secchi disk register, high turbidity, and Z_d/Z_p relationship values (Fig. 6e, f). Despite these features, different factors influence the non-clear condition in each water body. In the case of La Brava and Los Padres lakes, the turbid condition is caused by cyanobacterial blooms (mainly *Anabaena aphanizomenoides*) which were associated with changes in water appearance but not with fish mortality. Several authors linked some land uses (urban settlement and agriculture) with a high frequency and/or duration of these cyanobacterial blooms (Pizzolon et al. 1999; Quiros and Drago 1999). On the other hand, the presence of suspended sediment particles due to the inflow discharge into Nahuel Rucá Lake (Ondarza et al. 2012) and the trampling effect of livestock grazing on the littoral zone could be the main causes of the non-clear phase in this extremely shallow water body.

Referring to biological attributes, phytoplanktonic Chl*a* presented the same pattern in the three ecosystems, with higher values in the shallow lake or outflow stream sampling sites (Fig. 7a). Despite the shallow lakes being in a turbid phase during the sampling period (two of them with the presence of cyanobacterial blooms), mean phytoplanktonic Chl*a* scores resulted minor than those reported by Quirós et al. (2002b) for turbid Pampean lentic water bodies. While this fact seems to be incongruent with the one mentioned above, the presence of *A. aphanizomenoides* during all the study period in higher densities than those reported by Izaguirre and Vinocur (1994), confirms the non-clear state of these ecosystems.

Similar periphytic Chl*a* scores, with lower values in the outflow stream sampling sites, were detected in the intermountain ecosystems (Fig. 7b). In contrast, these concentrations were lower in Nahuel Rucá Lake, and the highest values were recorded in its outflow stream. In each water body, periphyton growing on *S. californicus* had a high detritus proportion with heterotrophic organisms and a minor fraction of autotrophic ones (Table 6). Secchi disk measurements mainly indicated that only a small percentage of water columns was illuminated, causing heavy light attenuation conditions in each aquatic habitat (Esquius and Escalante 2012). Under this scenario, the non-autotrophic organisms (mainly bacteria and microinvertebrates) dominated the periphyton community, restricting the presence of autotrophic ones to the subsurface portions of *S. californicus* stems (Esquius et al. 2010).

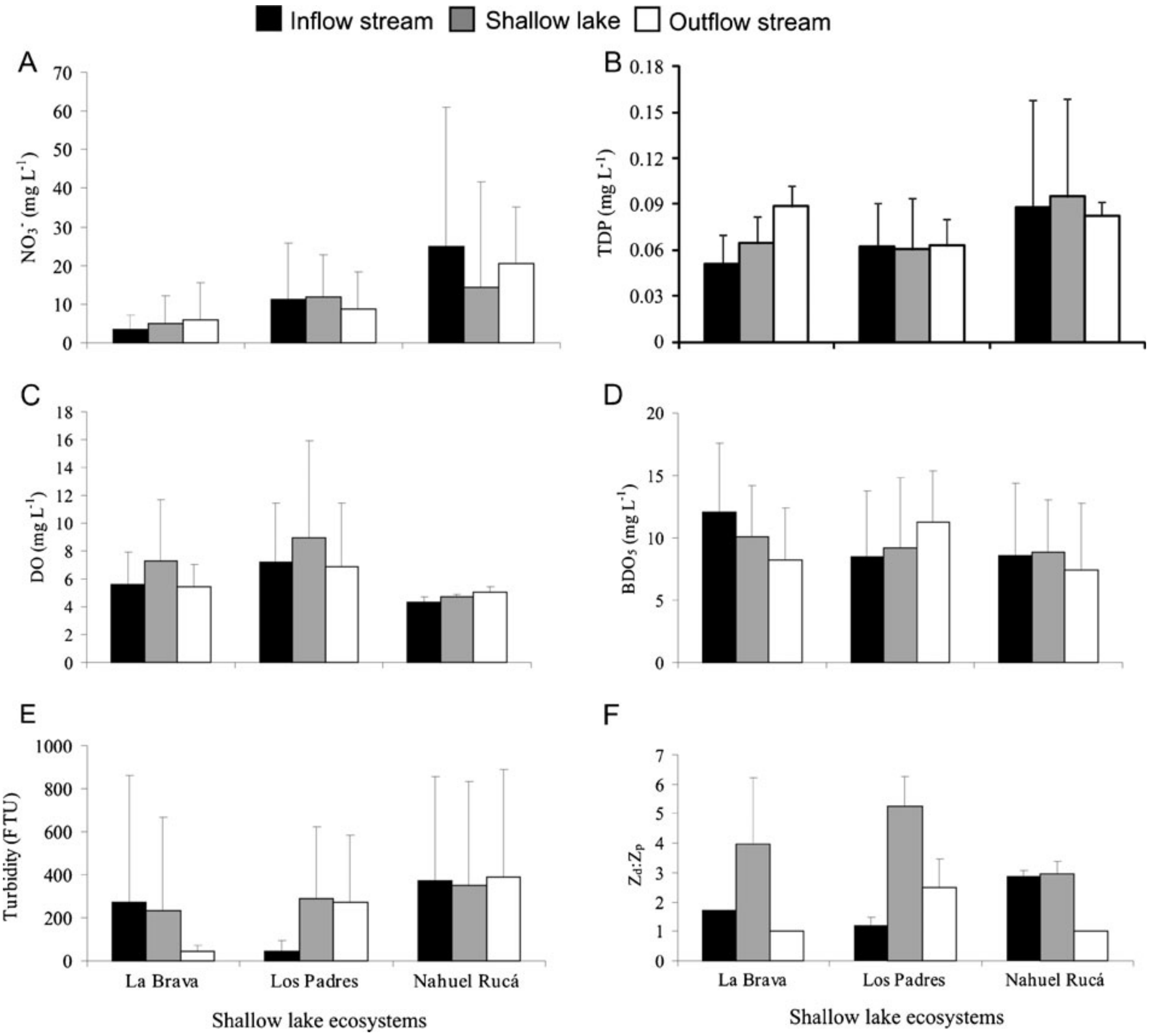

Fig. 6 Main physicochemical parameters of each shallow lake ecosystem: La Brava, Los Padres, and Nahuel Rucá lakes. **a** Nitrate concentration (NO_3^-, in milligrams per liter), **b** total dissolved phosphorus (*TDP*, in milligrams per liter), **c** dissolved oxygen (*DO*, in milligrams per liter), and **d** biochemical oxygen demand (*BOD*$_5$, in milligram per liter), **e** turbidity (in formazin turbidity unit (FTU), and **f** depth/photic depth relationship (Z_d/Z_p)

Periphytic DW values were quite similar in the intermountain ecosystems but lower in comparison to Nahuel Rucá Lake scores (Fig. 7c; Table 6). In general terms, the lowest values were detected in the inflow streams mostly due to the abrasive effect of the solid particles suspended in the water column which destabilize the substrate and prevent periphyton settlement (Esquius and Escalante 2012). The maxima DW values were found in La Brava Lake and in the outflow streams of La Tapera and Sotelo due to the higher water stability here observed. As we previously pointed out, these outflow streams have small gates in their headwaters that cause a marked reduction of water flow velocity, enhancing algal accumulation into the periphyton matrix (Esquius et al. 2010).

Concerning ash amount, the periphyton inorganic–organic type was dominant in most sampling sites while the organic–inorganic type was restricted to Tajamar Stream and Nahuel Rucá Lake (Table 6). While sediment accumulation could play an important role in community structure, a higher percentage of inorganic material storage in the periphytic mucilaginous matrix

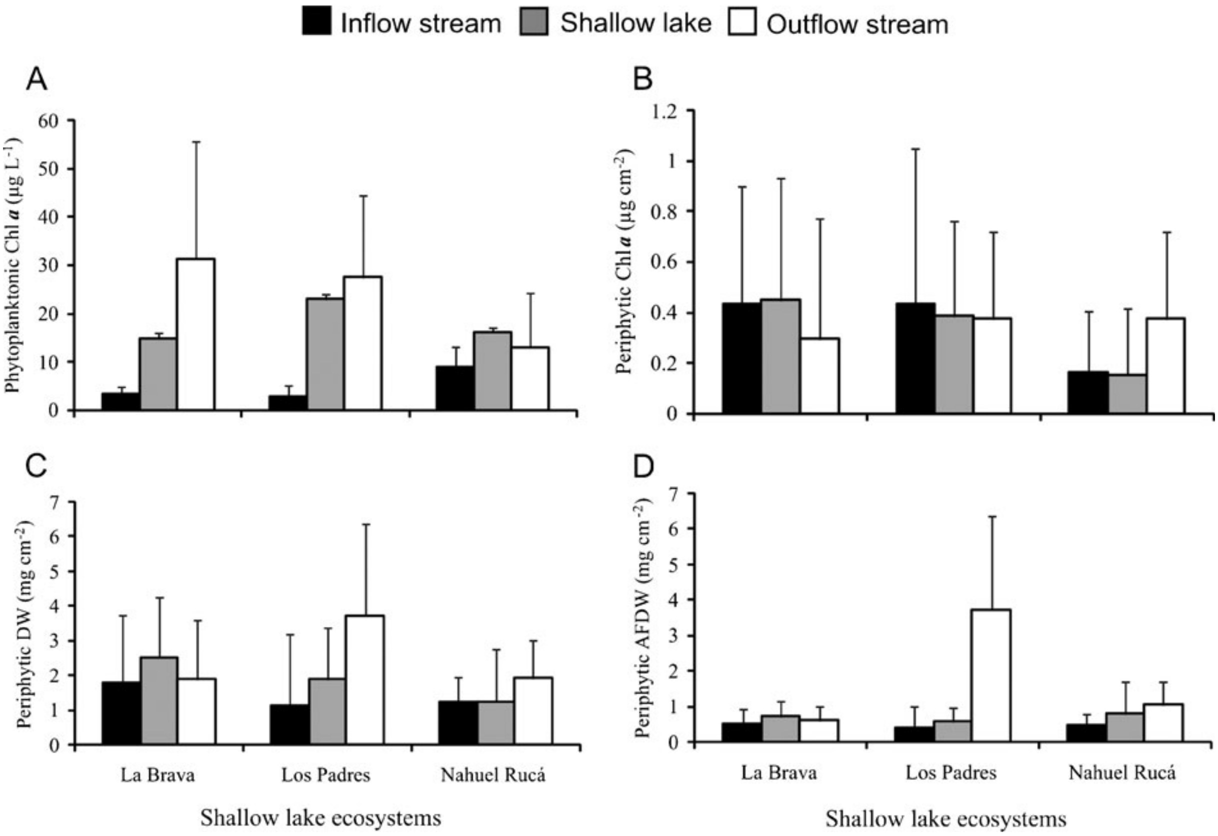

Fig. 7 Biotic attributes of each shallow lake ecosystem: La Brava, Los Padres, and Nahuel Rucá lakes. **a** Chlorophyll *a*, **b** dry weight, **c** ash free dry weight of periphyton upon *S. californicus*, and **d** phytoplanktonic chlorophyll *a*

could indicate a poor water quality (Fernandes and Esteves 2003). Extensive and intensive agriculture produce a noticeable decrease of soil structural stability and contribute to surface runoff (Borrelli et al. 2011), since these activities require heavy traffic of machinery in the field. These land cover types enhance the soil erosion risk more than pastures or natural grassland (Ometo et al. 2000), explaining such differences in the periphytic ash amount registered in each sampling site. Also related to this fact, periphytic AFDW values did not show differences among the sampling sites, with a minor percentage of material storage in the periphytic mucilaginous matrix corresponding to organic components (Fig. 7d).

Conclusions

The GIS-based Lake Pollution Hazard Index aimed to evaluate potential pollutant loads (i.e., especially dissolved salt, agrochemicals, nitrogen, and phosphorus) to the surface water resources as a consequence of human impacts and natural medium features in complex ecosystems, given that they constitute multipurpose zones used for recreational, residential, and intensive agricultural activities. In this context, threats to resource availability and quality could generate both an increase in the dissatisfaction of water users and a consequent change in land and water use behavior of people in the area.

This index was proposed for field staffs, watershed planners, and land users, not only for assessing and mapping the pollution hazard for shallow lake ecosystems in a sector of the Pampa Plain, but also to provide the ability to capture spatial variations and quickly reflect changes in potential pollutant load allocation to surface water in response to changes in the environment. Obtained information by the LPHI calculation is useful for performing a local diagnosis of the potential pollution hazard to a freshwater ecosystem. This map is important for providing a context to activities carried out by both decision makers and stakeholders involved in planning

Table 6 Periphyton types according to Lakatos System from each sampling site

	Mass type	Ash type	Chlorophyll *a* type
La Brava Lake			
EP	Small[a]	Inorganic–organic[a]	Heterotrophic
WLB	Medium[a]	Inorganic–organic	Heterotrophic
TJ	Medium[a]	Inorganic to organic–inorganic	Heterotrophic
Los Padres Lake			
LP	Small[a]	Inorganic–organic[a]	Heterotrophic
WLP	Small[a]	Inorganic–organic[a]	Heterotrophic
LT	High[a]	Inorganic–organic[a]	Heterotrophic
Nahuel Rucá Lake			
DC	Small	Inorganic–organic[a]	Heterotrophic
WNR	Small[a]	Organic–inorganic[a]	Heterotrophic
ST	Medium	Inorganic or inorganic–organic	Hetero-autotrophic

[a] With exceptions

Mass type (on the basis of DW): high mass (>4 mg cm^{-2}); medium (2–4 mg cm^{-2}), and small (<2 mg cm^{-2}). Ash type: inorganic (>75 %), inorganic–organic (50–75 %), organic–inorganic (25–50 %), and organic (<25 %). Chlorophyll *a* type (on the basis of periphytic chlorophyll *a*): autotrophic (>0.60 %), auto-heterotrophic (0.25–0.60 %), hetero-autotrophic (0.10–0.25 %), and heterotrophic (<0.10 %).

EP El Peligro Stream, *WLB* La Brava shallow lake, *TJ* Tajamar Stream, *LP* Los Padres Stream, *WLP* Los Padres shallow lake, *LT* La Tapera Stream, *DC* Dulce Stream, *WNR* Nahuel Rucá shallow lake, *ST* Sotelo Stream

and developing management and land use, respectively, in order to implement basic guidelines to improve lake sustainability. According to the results, the water management measures proposed to be applied to these complex systems, with multiple ownership status, uses and involved stakeholders, are: (1) water quality evaluation, (2) aquifer, streams and shallow lake monitoring, (3) construction of buffer zones including the shallow lake and the inflow stream (which acts as a source of recharge to the lake), (4) guidelines on agrochemical management and utilization, (5) better regulation and control of uses in the area by provincial and district authorities, and finally (6) promotion of environmental education and awareness in order to involve stakeholders in the planning process. In particular, in the ecosystems under studio, the water monitoring network should include the water recharge areas to the shallow lakes and sites with certain land cover type (such as discontinued urban fabric or sport and leisure facilities).

The application of the GIS-based LPHI in the three shallow lake ecosystems of the southeastern Pampa Plain and the examination of the anthropogenic and natural medium influence on their biophysical parameters allowed elucidating some relationships between lake conditions and land use in the region. The evaluation of the LPHI map suggests for La Brava and Los Padres lakes the highest pollution hazard with also high dissolved oxygen, BOD_5, and periphytic Chl*a* scores, the presence of cyanobacterial blooms and dominant inorganic–organic periphyton. Contrarily, Nahuel Rucá Lake seems to be the less hazardous water body with high NO_3^- and TDP values, absence of algal blooms, and organic–inorganic periphyton.

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