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CASE REPORT

An ecohydrological adaptive approach to a salt lake in the semiarid grasslands of Argentina: future management perspectives

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Abstract Past extreme hydrological events, future climate change scenarios and approaches for lake management were studied in the Argentinean Pampa. Anthropogenic climate change will impact water bodies and create enormous challenges for water management. Adaptation strategies are needed urgently to deal with the uncertainties originated by climate change on inland or coastal basins. Only a few studies have addressed practical strategies to mitigate global change impacts on lakes and practically none in South America. The purpose of this work was to discuss management options and seek better adaptive alternatives for the nature reserve Lake Chasicó, and to propose future management experiments and actions at a regional level. The ecohydrological approach is likely to increase the ecological resilience of the lake, dampen climate-driven hydrological variations and reduce eutrophication problems. Future projects should include wetland creation, fish management, water quality control, engineering work studies and education programs. Ecohydrology as an integrative natural science should be considered as a water management strategy to build ecological resilience into water bodies. The building of social-ecological resilience is also crucial for the stability of coupled human-ecological systems. The integration of natural and social sciences into sustainability approaches represents a robust strategy for adapting to climate change.

Keywords Adaptation strategies · Environmental management · Eutrophication · Ecohydrology · Climate change · Resilience

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Introduction

There is ample evidence of the ecological impact of recent climate change, from polar terrestrial to tropical marine environments (Walther et al. 2002; Parmesan 2006). Coastal zones are particularly vulnerable to environmental changes and are frequently under stress because of human population growth and socio-economic development. Coastal water bodies usually present high biological productivity, diversity and rate of change. Particularly, closed basin lakes are highly sensitive to climatic changes and therefore, respond more quickly to precipitation and to changes in temperature. Under often diverging climate change scenarios, the successful long-term management of water bodies presents considerable challenges.

The capacity of hydrologic basins ecosystems to absorb human and natural impacts can be improved through holistic management, which includes uses of biodiversity to build adaptive management, green technology and ecological resilience (Carpenter et al. 2006). Since the original definition of resilience for ecological systems (Hollings 1973), several concepts of resilience within the natural and social sciences are currently espoused (Brand and Jax 2007; Bueno and Basurto 2009; Kim and Oki 2011). This work refers to the definition of Walker et al. (2004), in which ecological resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity and feedbacks. This concept recognizes the presence of multiple stable states (Gunderson 2000) and is appropriate for the alternative states of shallow lakes (e.g., turbid or clear). Adaptative strategies are needed to increase the ecological resilience of water bodies and to buffer climatic disturbances.

Although considerable research has focused on climate change and its impacts, to date relatively little work have been conducted on practical strategies for adapting to it (Hulme 2005). Adaptation to climate change involves unprecedented methodological challenges because of the uncertainty and complexity of the hazard (Füssel 2007). Climate change should nowadays be considered as a driving force in water management decisions, which should integrate new approaches and methodologies able to flexibly handle issues of water quality and availability problems (Sahoo and Schaldow 2008). In this sense, ecohydrology has been proposed for the holistic adaptive management of aquatic systems.

Ecohydrology offers a variety of tools for basin and coastal management under the uncertain evolution of the combined effects of climate change and anthropogenic pressure (Wolanski et al. 2004). The ecohydrology concept was developed within the framework of the UNESCO International Hydrological Programme IHP-V (Zalewski et al. 1997) and is defined as an integrative science focused on the effects of hydrological processes on biotic processes and vice versa in freshwater and costal-zone ecosystems (Zalewski 2002). Its methodological principle is the use of ecosystem properties for water management, where the whole catchment is conceptualized as a "superorganism" possessing ecological resilience and resistance to stress.

Water management at the watershed level is seldom used in Argentina (Quirós and Drago 1999)—the second largest country in South America and, to a large extent, with a semiarid climate. The adaptive capacity of socio-economic systems in Latin America is very low, whereas the vulnerability to extreme climate events is high (Mata et al. 2001). Furthermore, while developing countries carry a great part of the global costs of climate change, rising atmospheric greenhouse gas concentrations are mainly the responsibility of industrialized countries (Mertz et al. 2009). Climate change is posing serious challenges for water management in arid and semiarid areas (Thompson and Flower 2009). Therefore, one of the major issues that policy makers, scientists, stakeholders and public in general now confront is how to assess complex and uncertain climate-driven responses.

The adaptive management of unstable water resources at the proper scale is critical in semiarid regions, particularly when long hydrological data series are scarce, as is frequently the case in South America. This precludes differentiation of superimposed local, regional and global trends, resulting in erroneous short-term policies based on a rationale derived from main shifting environmental baselines, either occurring or remembered by most decision makers. This is ultimately the case of recurrent floods of the last three decades in the Argentinean Pampa (Lara 2006). For example, several approaches have been proposed for the management of Lake Chasicó—a hydrologically and ecologically highly unstable lake located at the northernmost coastal limit of Patagonia. The aim of the present work is to assess management strategies to reduce the vulnerability of Lake Chasicó to climate change and to propose future management options and measures.

Study site

Lake Chasicó is a salt (salinity $\sim$20 g L^{-1}) water body in the semiarid region of the Argentinean Pampa. The only affluent of this lake is the River Chasicó. Situated in a large topographical depression, Lake Chasicó is, at 20 m below sea level, one of lowest water bodies of South America. Pampean lakes are characterized by being shallow, eutrophic and hydrologically unstable. Lake Chasicó, together with Salinas Chicas (a saltern) and the Vidriera Salitral (a salt marsh), is related geomorphologically to the Bahía Blanca estuary (Fig. 1). During the Holocenic transgression the Vidriera Salitral was likely a tidal channel connecting the sea with the Chasicó basin, which has been isolated from any marine influence for ca. 3,000 years. In recent decades with rainfall above the historical average, some management projects have proposed the creation of a derivation channel to connect the River Chasicó through the Vidriera Salitral marsh with the adjacent estuary or further upstream with Bahía Blanca city. During drought periods, this city suffers recurrently severe water shortages. Lake Chasicó has been classified as eutrophic with clear waters, and toxic Cyanophyta (cyanobacteria or blue-green algae) were described to be responsible for mass mortalities of the commercially important fish *Odontesthes bonariensis* (Kopprio et al. 2010). The future of the lake is nowadays endangered by natural and anthropogenic changes and latent use-conflicts.

Hydrological changes in the twentieth century

During the last century, two devastating climatic events (extreme droughts and floods) affected deeply the

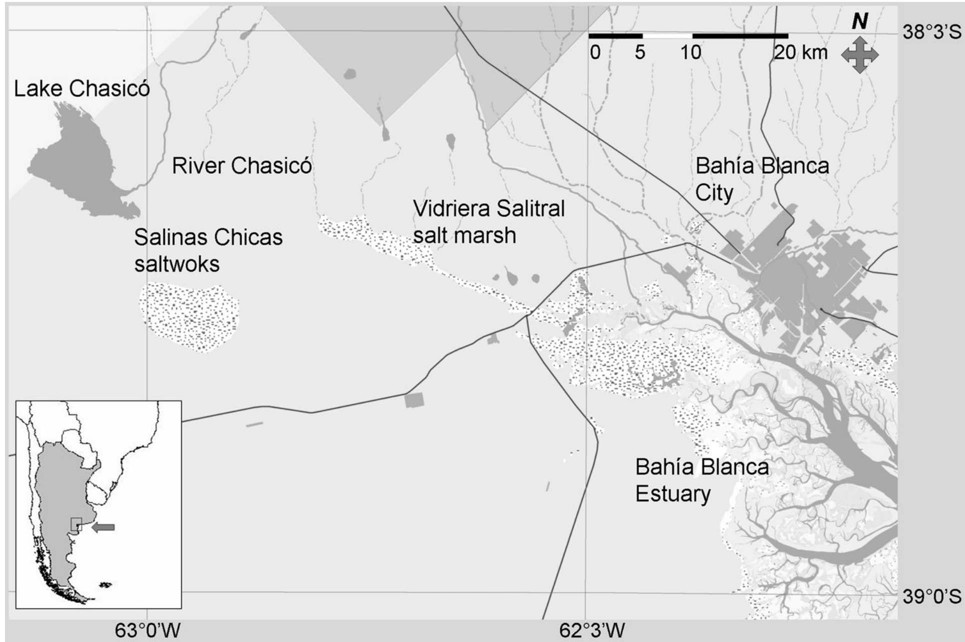

Fig. 1 Location of the study region. Lake Chasicó, Salinas Chicas and the Vidriera Salitral are related geomorphologically to the Bahía Blanca estuary

socio-ecological systems in the Pampa region (Viglizzo and Frank 2006). The first event took place during the 1930s and the 1940s. Throughout these two decades, rainfall in the whole area diminished by, on average, 200 mm $year^{-1}$. Droughts, deforestation, overgrazing, overcropping plus a non-suitable tillage technology in interaction with extremely dry and windy conditions caused soil degradation, severe dust storms, cattle mortality, crop failure, farmer bankruptcy and rural migration. The second crisis occurred after the 1970s, when in contrast to the first event, a significant increase in rainfall produced recurrent episodes of flooding. High cultivation rates increased the severity of floods dramatically during such humid periods. The configuration of dunes with respect to the slope, and the lack of a suitable infrastructure, impeded water drainage and favored its accumulation.

At a global scale, during the last three or four decades of the twentieth century, dry conditions and water withdrawal for human use produced long-term shrinkage of several basins located in arid or semiarid regions. The area of Lake Chad, a hydrologically closed system in North Africa has decreased by more than 90 % in the last 40 years (Elisa et al. 2010; Shen and Chen 2010). Other cases with similar droughts problems are the Niger, Volta and Senegal basins (Oyenbande and Odunuga 2010) and the Katuma River–Lake Rukwa systems (Elisa et al. 2010) in Africa; the Aral Sea and the Dead Sea in Western Asia (Oren et al. 2010); the Tarim basin in Western China (Shen and Chen 2010) and several salt lakes in Australia (Timms 2005). Conversely, the pampean lakes in Argentina have undergone the effects of increasing rainfall and severe floods.

Lake Chasicó is partially surrounded by dunes and belongs to an endorheic basin especially sensitive to hydrologic oscillations. The lake thus responded with dramatic changes in its size and salinity. In 1963 the lake had an extension of about 3,000 ha and a salinity of about 100 g L^{-1}. Due to its very high salt content, the lake was used primarily for recreational and therapeutic bathing. Some farms, mainly carrying out cattle breeding, were situated close to the lake. Since the 1970s several inundation events have occurred and the inundation peak of the 1980s coincided with one of the strongest El Niño events of the century (Lara 2006). As a consequence of the wet phase from 1970 to 2005 (Fig. 2), the lake expanded by about 400 % (~12,000 ha) and its salinity decreased to 20 g L^{-1}.

The large expansion of Lake Chasicó (Fig. 3a), resulted in significant losses of agricultural land, complete submersion of a touristic village, and the threat of flooding of large neighbouring saltworks. Simultaneously, the reduction in lake salinity produced a drastic biomass increase of *O. bonariensis* (silverside, pejerrey), due to moderate salinities that favor growth of the larvae and juveniles of this species (Tsuzuki et al. 2000). As a consequence, this lake experienced a few years of high fish biomass, with large and abundant specimens (Fig. 3b), which reached their maximum registered possible sizes and weights. The fish attracted sport fishermen from the whole country and offered an alternative economical activity for people affected by the floods. In order to protect the fish population and the biota of the coastal zone, Lake Chasicó and adjacent terrestrial ecosystems were declared a nature reserve.

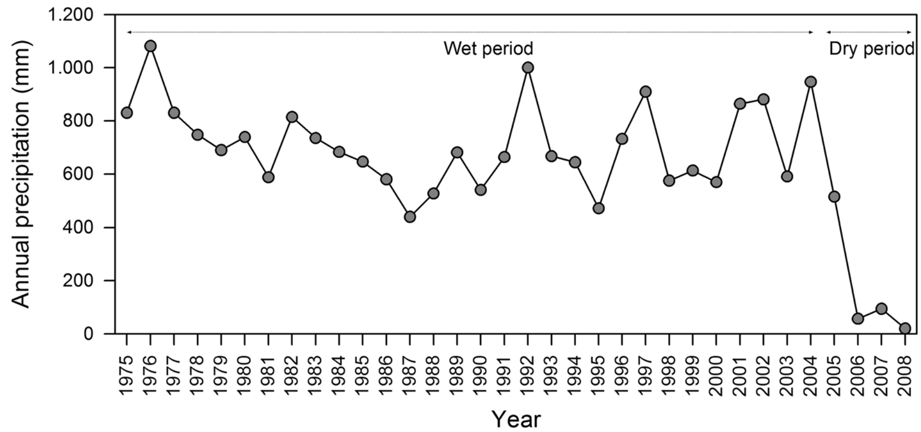

Fig. 2 Annual rainfall (mm) in Bahía Blanca city located about 60 km to the west of Lake Chasicó: wet and dry phases

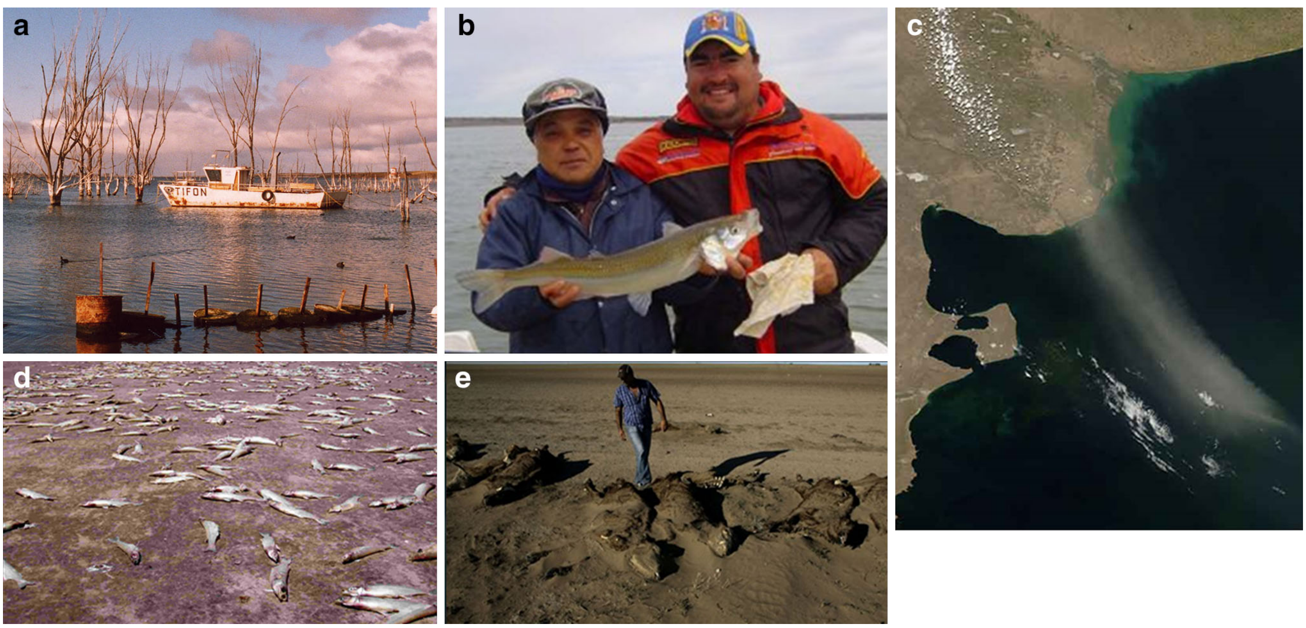

Fig. 3 **a** Land flooding due to strong expansion of Lake Chasicó in the wet period. **b** Decreased lake salinity resulted in the rapid development of high biomass of *Odontesthes bonariensis* with abundant and large specimens. **c** Dust bowls originated by the severe drought produced soil erosion and loss of vegetation coverage in the south of the Pampa. **d**, **e** Fish and cattle mortality related to the drought. Source: http://www.travesiadepesca.com (**b**, **d**)

Current situation

In recent years, sport fishing, together with related eco- or standard tourism in pampean lakes have been more profitable than traditional cattle farming. However, since 2006 a severe drought has begun to affect the region, damaging the agricultural structure of the semiarid grasslands dramatically, with high cattle mortality, loss of vegetation coverage and soil erosion in the south of the Pampas (Fig. 3c, e). During this dry phase (Fig. 2), the Pampa region has undergone the worst drought in recent decades.

The drought period worsened the natural eutrophic state of water bodies and increased their salinity. Pampean lakes suffered fish mortality, most probably due to the impacts of eutrophication such as toxic cyanobacteria blooms or anoxia (Fig. 3d). Recent studies on historical climate strongly suggest the current onset of a dry phase that could last 25–50 years (Viglizzo and Frank 2006). This could lead to an increase of lake salinity beyond tolerable limits for its fish populations; increased overall estuarine salinity and reduced freshwater supply for direct human consumption, agriculture and industry. This situation could induce a socio-economical crisis in a region with recurrent freshwater shortages due to an appropriate infrastructure and, paradoxically, strong industrial development in Bahía Blanca city.

Several possible management approaches for Lake Chasicó have been proposed during the last years of the wet period without considering different future scenarios. However, since the end of the last climate phase, with the exception of isolated voices from academia, no institutional discussion has taken place on how to deal with pampean water bodies, in case the current trend should indeed develop to an extended dry period. A common pattern among the policy makers has been the consideration of one main aspect, and short-term reasoning based on the decadal nature of the respective period. Hence, some solutions considered only the main trend occurring and being remembered by most actors, such as the recurrent floods of the last three decades. We discuss here management challenges and possible climatic impacts.

Discussion

Management challenges: socio-ecological background and climate change impacts

The above-mentioned approaches address as main issues the lost of agricultural land, the hydrological instability and associated uncertainty of investment strategies, and possible damage to neighboring saltworks due to lake overflow. Further, freshwater availability and the potential effects of warming and agricultural runoff on toxic algal blooms and fish mortality, as well as salinities in suboptimal ranges for fish development are all of socio-ecological concern.

For Lake Chasicó and similar aquatic ecosystems, the nature of some effects of climate change are similar to those associated with eutrophication (Mooij et al. 2005; Adrian et al. 2009). An increase in the deterioration of benthic primary producers, the declining ecological status and emergence of eutrophication processes are to be expected as a consequence of climate change in many coastal lagoons (Lloret et al. 2008). Worldwide reports of Cyanophyta blooms, as well as the number of toxins and toxic species in aquatic systems have increased considerably (Anderson 2009). In their strategies, water managers will have to deal with the expansion of cyanobacterial blooms (Paerl and Huisman 2008). Besides their toxic effects, Cyanophyta are low-quality food, which decouples trophic webs and which can be detrimental for the growth of zooplankton and fish.

Additionally, climate change may decouple phenological relationships, altering trophic structures and eventually leading to ecosystem-level changes (Edwards and Richardson 2004). For example, enhanced predation pressure by fish would increase nutrient loading by decreasing the density of large-bodied zooplankton and thus the top-down control of phytoplankton. Increases in phytoplankton will reduce the chances of maintaining the clear water state of these ecosystems (Brucet et al. 2010). Fish predation on zooplankton and its effect on phytoplankton are very intense in pampean lakes (Sosnovsky and Quirós 2009). Elevated temperatures will lead to lower oxygen content in water and higher respiration rates of autotrophic organisms during the night, animals and bacteria. More frequent anoxia events are expected to cause fish mortalities under climate change scenarios. The anoxic bottom favored also a higher release of ammonium and phosphate, worsening eutrophication problems.

Climate change will likely increase the frequency of floods or droughts (IPCC 2007) and result in a new balance of water in endorheic lakes. Rodrigues Capítulo et al. (2010) considered only the occurrence of higher rainfall and flooding events in future climate change scenarios in the lakes of the Argentinean Pampa. However, taking into account the history of this region, the increased evapotranspiration due to higher temperatures, the uncertainty of the climate projections and interaction with globally acting phenomena (e.g., ENSO oscillations), this region will be likely more endangered by mid- to long-term droughts. Furthermore, drought is considered as one of the most complex but least understood of all natural hazards, affecting more people than any other climate event (Shahbazbegian and Bagheri 2010). Worldwide, many permanent salt lakes have decreased in size and increased in salinity (Jellison et al. 2008). Therefore, hydrological uncertainty should be considered as a key criterion in the management of pampean lakes.

Possible solutions, approaches and conflicts

Channel

In order to prevent floods during the "wet period", some projects have proposed the construction of a channel connecting the River Chasicó to the Bahía Blanca estuary through the Vidriera Salitral (Fig. 1). This would allow a straightforward control mechanism in case of rainfall increment, avoiding further land inundation, overflow of the lake and flooding of the saltworks. Since it is a low-cost measure, this option was officially favored by local Municipal authorities. However, an alleviation channel alone lacks the hydraulic tools to react to drought situations, e.g., by regulating salinity, nutrient, level and stratification in order to control toxic algal blooms or *O. bonariensis* dynamics. Further, the connection with the estuary could originate sea water intrusion during storms or, in the long-term, through sea level rise.

Dam

This initiative considers the construction of a dam for the creation of a regulating reservoir in the upstream catchment area of the Chasicó basin. This initiative was favored only partially by the local Municipal authorities. This approach implies inundation of agricultural land and indemnifications to farm owners. Furthermore, due to the flat-to-only-slightly-undulated pampean topography, such a reservoir alone would probably not be capable of retaining a large runoff due to excess rainfall above the average for a period of several decades, as occurred in the period 1970–2000.

Dam and channel

This approach was conceived in order to improve the overall water supply to increase human and industrial water requests in the region. The project involved dam construction on the River Chasicó and a channel for connecting the reservoir to Bahía Blanca. The initiative was favored by the State Government, who demanded implementation from the private operating water supplier. However, it was not supported at the Municipal level. Besides, water suitability for such an approach has not been assessed thoroughly. Little information is available on seasonal variations of arsenic, fluoride and silicate concentrations in River Chasicó waters. This river has a large water input from the aquifer, and pampean groundwater can present quality problems due to high concentrations of potentially harmful elements such as, e.g., arsenic, fluoride, nitrate and selenium (Smedley et al. 2002). High silicate values in water often preclude its use in industrial processes. Further, the State's initiative is not compatible with the Municipal intention considering the purpose of the dam, since it does not take into account the level regulation of Lake Chasicó and considers only freshwater demands. Therefore, this lack of coordination between Municipal and State strategies would inevitably lead to a conflict of interests during hot summers or drought periods, when water would be needed for both the lake ecosystem and urban areas.

Ecohydrology approach (dams, channels and wetlands)

A schematic view of this approach, with its advantages and shortcomings is shown in Fig. 4. Instead of only one dam, the establishment of several interconnected buffer lakes by dams constructed upstream of the River Chasicó, would permit an all-year level regulation of Lake Chasicó, damping major oscillations through controlled water retention and release according to differential topography and rainfall regimes along the basin. Aquifer loading and water reserves would mitigate the impact of droughts on land use and lake dynamics. This is important not only for reducing lake salinity increments; even at optimum salinity values for fish population, eventual summer stratification and derived toxic blooms could be mitigated by pulsed water release (Wolanski et al. 2006). Further, eutrophication itself, as well as the associated toxic bloom risk in the lake could be avoided by regulating phosphorus input. Wetland propagation in the catchment area would generate favorable conditions for nutrient retention in marsh vegetation and habitat creation for local fauna. Regulated fishing effort in the lake would help control fish populations and increase zooplankton abundance, which will top-down adjust phytoplankton density, favoring the clear state of the lake. A network of channels could be used for linking reservoirs and selectively feed or drain wetlands according to their needs, supply freshwater to the urban region and, in case of extreme flood events, derivate water flow through Vidriera Salitral to the Bahía Blanca estuary.

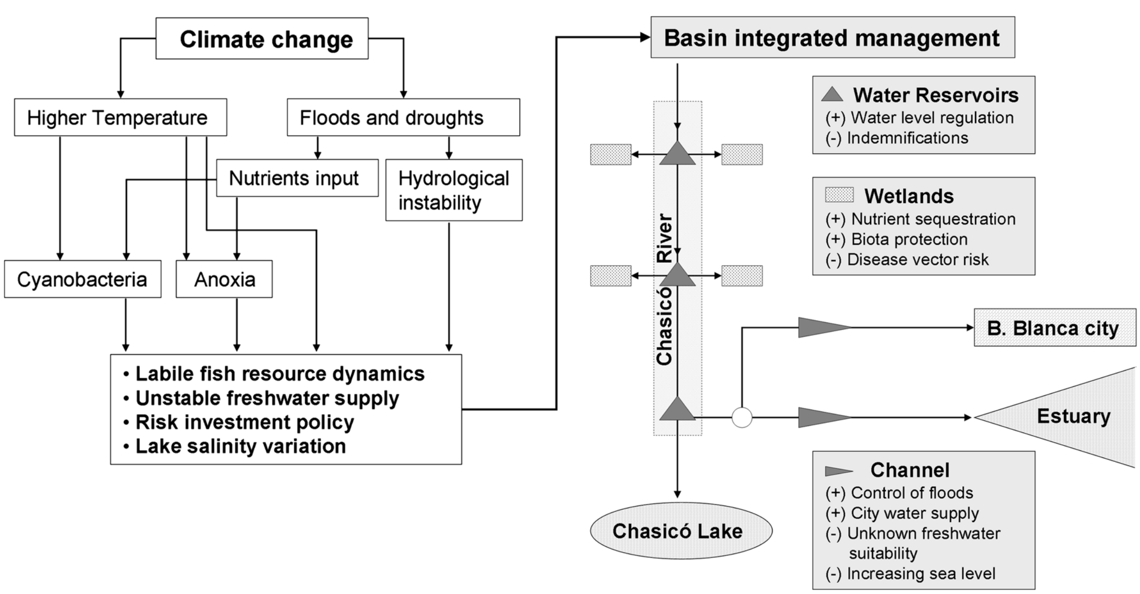

Fig. 4 Schematic view of the ecohydrological approach: *left* driving forces and target problems of the study case, *right* a whole-basin management strategy

Such an approach also implies inundation of agricultural land and subsequent indemnification programs. However, adequate marsh management can optimize nutrient retention and harvesting of plant biomass production for direct cattle feeding or fodder storage, thus providing shelter for animals and/or mitigating the effects of droughts in semiarid regions. It has to be kept in mind that wetland creation also implies an unknown risk of disease vector proliferation, e.g., mosquitoes. Moreover, higher temperatures, changes in precipitation and wind regimes would alter the geographical range and seasonality of transmission of many vector-borne diseases (McMichael 2003). Thus, this potential hazard has to be included from the very beginning as a criterion for the design of the individual wetland areas and the connectivity among them. Available techniques for mosquito control such as runneling and Open Marsh Water Management (OMWM) can control mosquito proliferation effectively and promote habitat enhancement for marsh fish and wildlife (Lara et al. 2011). The use of these techniques at a wetland scale (a few hectares), as well as the whole-basin management plan (hundreds to thousands of hectares) requires high-resolution digital elevation models in order to be able to control and predict water fluxes under different hydrological settings or scenarios.

The proposed ecohydrological approach could increase the resilience of the lake ecosystem and help mitigate some of the effects of climate change, including the damping of hydrological oscillations and eutrophication-like impacts on biota. The more stable situation would allow long-term planning, lower investment risk and more sustainable economic development. Moreover, the discussion on the situation at Lake Chasicó and other water bodies in the semiarid region should consider, besides purely hydraulic aspects, also the regulation of physico-chemical and trophic parameters, aiming at a sustainable management of the fish resource and the prevention of occasionally occurring toxic algal blooms and fish mass mortality. Despite the complexity of this strategy, small-scale pilot research management projects are possible, with low risk and conflict potential and, to our understanding, they represent essential steps for moving from fragmented to coordinated and adaptive water management, including both scenarios of alternating prolonged wet and dry phases.

Such interdisciplinary small-scale projects should be implemented urgently in the semiarid pampean region before further severe damage occurs, such as that occurring in the last 4 years. This project should also include future actions and management experiments such as the creation of a small wetland, the management of fish population, the control of water and plankton, and the intensification of research related to dam and channel construction. Scientific assessments play a key role in improving decision-making regarding global change (Polasky et al. 2011) and future research needs for climate change experiments in ecology (Jentsch et al. 2007). Moreover, better coordination among the various actors in Lake Chasicó together with education and divulgation programs are essential to attain sustainable management and an effective risk response. Ecohydrology provides the framework for a conceptually solid and operatively feasible integration of these items.

Future management experiments, actions and studies

Small wetland

Wetland creation involves several ecological issues and a few hectares along the river or near the lake could be selected to assess system response. This scale project would allow assessment of the increment in wildlife biodiversity or the risk of loss of habitat of endangered species, and the suitability and efficiency of the native flora to remove nutrients and to tolerate stressful conditions (e.g., salinity or extreme hydrological variations). The monitoring of wetland development is essential for long-term success, including the evaluation of associated disease risk vectors, the time required for full functional activity and its reaction under a changing climate. Exploration of phytotechnologies relying on direct below-ground absorption of nutrients can provide alternatives to construction of open wetlands reducing disease vector proliferation.

Fish management

O. bonariensis is a zooplanktivorous fish and has top-down control of zooplankton and indirectly of phytoplankton. Laboratory experiments will help elucidate the effect of climate-driven higher temperatures on *O. bonariensis* predation rate or efficiency. The population of *O. bonariensis* could also be reduced to its minimal sustainable size in Lake Chasicó, in order to observe the effect of increased zooplankton on water quality. Furthermore, the sex ratio of the *O. bonariensis* population should be monitored closely due to its thermolabile sex determination (Strüssmann et al. 1996), which may produce an increase in the male/female proportion under higher temperatures.

Water and plankton control

Periodical monitoring of water quality in the lake and in the aquifer is crucial to understand hydrological interactions and biogeochemical cycles. In addition to wetland creation, the management of Lake Chasicó basin should include a wastewater treatment from Village Chapalcó to decrease nutrient input. The suitability for human consumption and the presence of toxic elements such as arsenic should be evaluated in the groundwater and the river. Furthermore, is desirable to regulate groundwater extraction, because it is one of the main factors drying salt lakes in Australia (Timms 2005). The study of natural plankton communities and seasonal cycles in Lake Chasicó started recently (Kopprio et al. 2010, 2012). Yet, mesocosm experiments are necessary to assess plankton communities associated to changing environmental or nutritional variables. This experience should help address the theoretical increment on toxic or low food quality species such as cyanobacteria and help to understand the reaction of zooplankton or fish larvae to changing phytoplankton communities.

Dam and channel studies

Dam and channel studies are necessary to evaluate possible environmental impacts, the topography of the region, the transport of sediments in River Chasicó, and the geological suitability for these engineering works. The River Chasicó affects river food webs and ecosystem processes in Lake Chasicó; for this reason, the necessary water flow required to sustain the resilience of the system should be assessed. Once the dam is constructed, experimental high-flow dam releases should be implemented to increase understanding of how dam operations affect physical and biological processes, as it was implemented in Colorado River in the United States (Cross et al. 2011). A lack of consideration of minimal river environmental flows has impacted negatively on people and wildlife (Elisa et al. 2010).

Building social-ecological resilience

The social-ecological resilience is the amount of disturbance a system can absorb and still remain within the same state and the degree to which the system is capable of self-organization and can build capacity for learning and adaptation (Adger et al. 2005; Folke 2006). Social aspects are also critical for adaptation in complex and changing ecological systems. To be resilient in the context of climate change, societies must be able to buffer disturbance, to self-organize, and to learn and adapt (Tompkins and Adger 2004). During the floods of Lake Chasicó, there occurred practically the same case as that in the River Salado flooding event. There was no coordination within levels of government, there were many levels with shared and overlapping responsibilities in the basin and was a lack of experience of the different actors in working together constructively (Herzer 2003). Since mankind faces increased risk of extreme natural disasters (Yasuhara et al. 2011), regional coordination should be improved drastically and a specific function to each actor or political level should be assigned not only for administration, but also regarding responsibilities and courses of action concerning natural disasters.

The integration of society into management programs is crucial for adaptation to global change. The residents and tourists of Lake Chasicó, nonetheless, scarcely perceive future environmental problems (Zinger 2000) and the ecohydrological approach presented in this work will require installation of gates or pumps, which may be subject to vandalism. Moreover, population increases, economic development, and a changing climate will aggravate water conflicts and environmental problems. Education programs to increase the awareness of inhabitants and tourists of future environmental hazards are urgently needed.

Conclusion

Although all adaptation strategies have shortcomings, the ecohydrological approach seems to be the most comprehensive management option to increase the ecological resilience of Lake Chasicó system under changing climatic settings. A small- to mid-scale project should be performed to thoroughly evaluate its viability and undesired negative effects. This project should include the creation of a small wetland along the basin, control and further research on biological and hydrological variables, feasibility studies on engineering works and educational programs about future hazards. The enhancement of ecological resilience could be achieved by an adaptive management plan that can be modified on the basis of new information and complemented by measures to build social-ecological resilience. The social and natural sciences are complementary, and the integration of both into sustainability represents a powerful tool of adaptation to climate change in complex human–natural systems.

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