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DOI 10.1007/s11027-015-9650-3

ORIGINAL ARTICLE

Water security as a challenge for the sustainability of La Serena-Coquimbo conurbation in northern Chile: global perspectives and adaptation

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Received: 28 September 2014 / Accepted: 20 March 2015

Abstract The aim of this study is to address the problem of balance between water scarcity and sustainability, which are the key components of water security of cities located in arid lands, particularly those under constant expansion and population growth. In this paper, we have highlighted the problem of water security for the sustainability of the La Serena-Coquimbo conurbation (LSCC). The coastal LSCC is located at the outlet of the Elqui River basin, in the southern edge of the Chilean Atacama Desert. We have analyzed the available information including drinking water production and consumption data, groundwater levels, precipitation data and population data. Between the years 2009 and 2013 the total water consumption for the area has significantly increased. On the other hand, there has been a significant decrease trend in the precipitations and the groundwater levels show a decrease of about 30 m between the years 1995 and 2014. In a few years, this urban area could face a general water scarcity problem if the drought conditions remain unchanged and if the water demand trend for the agricultural, mining and drinking water continues its increasing. The cities located in the arid lands are particularly vulnerable to water scarcity because their populations are highly concentrated and requires reliable supplies of water to make possible human and economic activities. We discuss how adaptation of the arid land urban areas to water scarcity requires a range of solutions, including economic incentives, regulatory measures, and technology.

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Published online: 09 April 2015

Keywords Water scarcity · Urban planning · Drought and desertification · Global change · Groundwater · River basin · Sustainability · Water security · Adaptation · Aquifer depletion

1 Introduction

Water scarcity is the physical defining characteristic of the arid regions, the United Nations Intergovernmental Panel on Climate Change (IPCC) has emerged as particularly vulnerable to climate change (IPCC 2014a). The large-scale development of these regions, whether urban or agricultural, depends on the ability to pump groundwater over long distances, and desalinate brackish water and/or seawater. Global water extraction have increased more than sixfold in the last century, which is more than twice the rate of human population growth (Kahil et al. 2015). Urbanization also represents the human ecological transformation, where the human, spatial, and real relationship with the nature, contains the key for the sustainability (Rees and Wackernagel 1996; Collins and Bolin 2007; Fang et al. 2007; Srinivasan et al. 2013; Olmstead 2014; Grit et al. 2015). The need of more resources like food, soil and energy, to meet the requirements of expanding cities, makes necessary to include the natural resources of a city in the urban planning, in order to achieve a sustainable urban design. As water has become the shortest resource in arid, semi-arid, and rapid urbanization areas, when the water resources utilization has approached or exceeded its threshold, the socio-economic growth rate, the projected targets to eradicate poverty and the sustainable development are slowed down (Fang et al. 2007).

The multiple needs of this constant expansion and population growth, makes necessary to ensure the sustainable maintenance of the city, specially in arid and semiarid zones. Ma et al. (2005), describe the serious degradation of the ecosystem and the ground water, resulting, in particular, by large-scale water resources development associated with the dramatic total population growth, in the last 50 years in the arid zone of northwest China. They found tremendous changes in the ground water recharges, indicating the urgency of water resources management and allocation within the river basin to achieve sustainable development. Land altered by human activity represents radical changes in land use cover usually over long term such as wetland to urban settlement (Turner et al. 2007). This situation addresses the dynamics of land cover and land use, from a human and environmental perspective.

Since the United Nations Conference on Environment and Development, Rio de Janeiro, Brazil, 1992, the tripartite description that combines the three dimensions of sustainability (i.e., the environmental / ecological, economical, and social dimensions) has constituted the basis for most of the generally accepted definition of sustainable development, including international organizations (Lehtonen 2004). Sustainability is still understood as a multidimensional issue and, according to UNDP (2014), sustainability must cover all of these three dimensions. Hence, it is necessary to check the excessive pressure on natural resources and the vital services they provide in order to extend the welfare of all humanity and to guarantee for future generations (Rueda 1999).

Climate models project increased aridity in the twenty-first century over most of Africa, southern Europe and the Middle East, most of the Americas, Australia, and Southeast Asia, having large impacts on agriculture, urban, and industrial users, on tourism, and on ecosystems (Dai 2011; Xiao-jun et al. 2014; Kahil et al. 2015).Most of the world's future population growth will occur in water scarce areas and water stressed regions of the world, and also in the poorest areas (Gardner-Outlaw and Engelman 1999).

Water security indicates the ability of the society to ensure the water supply to meet the basic needs of water, conservation and sustainable use of aquatic and terrestrial ecosystems.

Water security is related to the ability to produce food without altering the quality and quantity of available water resources, and the mechanisms and social regulations to reduce and to manage conflicts or disputes over water (Avila 2008).

Current conflicts of access to water in Chile are structurally related to the implementation of the water management model established by the water code. The scarce water resources are allocated, according to the 1981 act, which emphasize the economic efficiency based on the principle of the right to transfer water rights among owners (Oyarzún and Oyarzún 2009). This instrument established a market for water rights, in which water rights are treated as any commodity, so they can be sold, rented, and transferred to other people (Hurlbert and Diaz 2013). The water code allocates water resources according to supply and demand criteria, having a severe pressure on water resources, specially in areas where the resources are scarce (SISS 2013). As a result, water rights have achieved peak market prices, on competition for water rights and the environmental effects of accelerated groundwater withdrawal (Oyarzún and Oyarzún 2009).

In Chile, desertification exacerbated by climate change, is the largest environmental problem affecting almost two thirds of the national territory, triggering land abandonment and urban migration (Salinas and Mendieta 2013a). Studies suggest that water demand management or water supply management by themself will not be able to adapt to an increased water stress. A combination of both, water supply and water demand management strategies is necessary in order to adapt to varying environmental and associated uncertainties (Wang et al. 2014). For this purpose, this work describes the situation of water availability and the growing population in a coastal urban area located in an arid zone in the north of Chile.

The protection of soils from erosion and the use of the best practices for the management of limited water resources, which are largely depending on the Andean snowmelt, are important issues for the sustainability of La Serena-Coquimbo conurbation (LSCC). As well as to avoid the overexploitation of the ecosystem services and to avoid uncertainties about the ecological sustainability and the sustainability of the city itself (Salinas and Mendieta 2013a).

The aim of this study is to address the problem of the balance between water scarcity and water sustainability, which are the key components of water security of cities located in arid lands.

2 Material and methods

2.1 Area of study: LSCC at the gates of the Atacama desert

The coastal LSCC is located at the outlet of the Elqui River basin, in the southern edge of the Atacama Desert (29°54′28″ S, 71°15′15″ W; Fig. 1). This is an area where the problem of the water shortage is more acute. On the other hand, there is a growing problem of water shortages mainly caused by a lack of precipitation in this area (SISS 2013). In this respect, LSCC is linked to a regional groundwater flow system, which is mainly recharged in the high part of the Elqui River Basin (Squeo et al. 2006).

LSCC is the main urban area of the administrative Region IV of Chile, and has 413,716 inhabitants according to the 2012 national census (i.e., 58.5 % of the total regional population of 707.654 inhabitants (INE 2012). LSCC has an arid climate characterized by a short wet season in winter and a dry season of 9 months. The average annual temperature is 13.5 °C, while the average maximum and minimum temperatures are 21 and 7 °C, respectively. The

Fig. 1 Location of La Serena-Coquimbo conurbation (LSCC) and El Culebrón-Lagunillas aquifer

average annual rainfall in years 1976–2014 is 170 mm, although a decreasing trend has been observed within this period of time.

The aquifer of the Elqui River basin is a regional waterbody mainly recharged in the high portions of the basin (Squeo et al. 2006). One of the sub-systems of this regional aquifer is the El Culebrón-Lagunillas aquifer, which is one of the main sources of water for the urban demand in LSCC. El Culebrón-Lagunillas aquifer covers a total area of 785 km^2 and it is divided, from north to south, in three interconnected sectors, i.e., Peñuelas, Culebrón, and Lagunillas. For the groundwater level data of the aquifer, we selected a representative monitoring well located between the Peñuelas and Culebrón sectors with the longest history of monitoring. To ensure the consumptive water rights for the existing users, the National Water Agency (DGA) promulgated a declaration of exhaustion, both for the entire aquifer and for the Elqui River and all its tributaries. Thus, the grant of new water rights in the basin is forbidden. Indeed, there are many other areas in Chile where water rights are no longer issued.

Available information including drinking water production and consumption data was provided by the Superintendency of Sanitary Services (SISS), groundwater level and precipitation data was provided by the DGA and population data was provided by the National Institute of Statistics (INE 2012).

2.2 Statistical test for trend detection

The significance of possible trends in hydrologic variables was evaluated using the Mann–Kendall test (Mann 1945; Kendall 1975).This is a non-parametric test widely applied in trend analysis of hydrological data (Yue and Wang 2004). We adopted a level of confidence of 90 %, commonly used in other hydrologic studies (Quintana and Aceituno 2006; Yenigün et al. 2008; Falvey and Garreaud 2009; Birsan et al. 2014). On the other hand, the rate of change, or slope, of the trend was estimated by the Sen's nonparametric method (Sen 1968), widely used for hydrological studies (Belle and Hughes 1984; Kahya and Kalaycı 2004; Khaliq et al. 2009).

3 Results and discussion

In the last decades there has been a decrease in precipitation in the region. Figure 2 shows the annual precipitation from 1976 to 2014 in the recharge area of the Elqui River basin, which shows a significant ($p \leq 0.1$) decreasing trend of precipitation according to the Mann–Kendall test.

The population data shows that between 2002 and 2012 the highest rate of population growth occurred in LSCC (i.e., 32.3 %, equivalent to 104.404 inhabitants) (INE 2012), as seen in Fig. 3.

According to the information provided by the SISS, in Region IV, the main water source is groundwater (i.e., 66 % of the total), in particular, part of the water consumption in the city comes from the El Culebrón-Lagunillas aquifer, in which there is an increasing pressure due to the expansion of the mining industry, agriculture and the growth of the city (Squeo et al. 2006).

Figure 4 shows the water production (cubic hectometer) in the Region IV, between years 2009 and 2013 (SISS 2013). Over this period, the total water production increased in 14.5 %, mainly due to the contribution of groundwater, which increased in 36 %. On the other hand, the contribution of surface water to the total production decreased in 19 %. All these trends were significant ones according to the Mann–Kendall test. According to the Sen test, the increase of the total water production is 2,12 hm^3 $year^{-1}$. The production based on surface water decreased at a rate of 1 hm^3 $year^{-1}$, while the groundwater based production increased at a rate of 3 hm^3 $year^{-1}$.

As many other parts of the world, the conflict over water resources in the Culebrón-Lagunillas aquifer shows the historic competition over water between urban, industrial, and agricultural uses (Gober 2010). In Chile, the competition of the different uses of water has resulted in the concentration of the consumptive water rights ownership on behave of the agriculture, the industry and the mining sector. Thus, the increasing demand of water for the

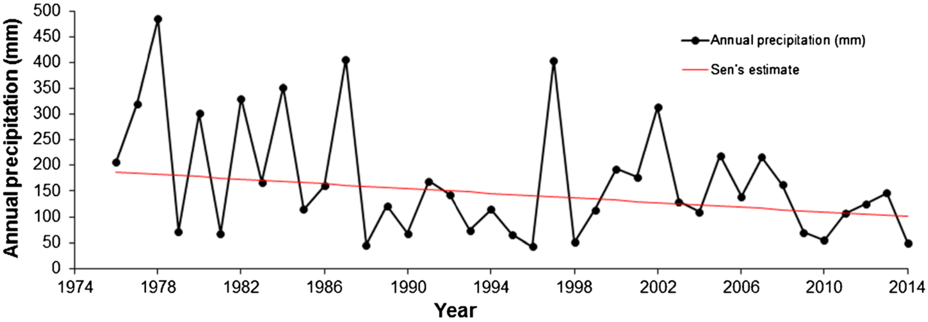

Fig. 2 Trend analysis of the accumulated annual precipitation (in mm) between years 1976 and 2014 in the upper part of the Elqui river basin system. Data from DGA database

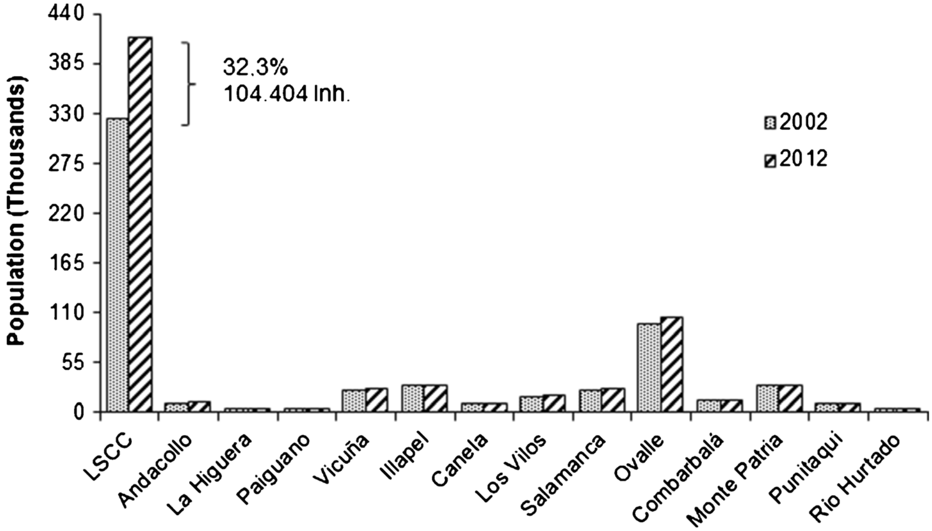

Fig. 3 Resident population for municipalities of the Region IV. Data from 2002 and 2012 Censuses

expansion of the LSCC and its industrial activities, not only affect other productive sectors, but also affect other surrounding urban communities. In this study area, the main water consumer is agriculture (67 %), followed by mining industry (19 %) and drinking water (14 %) (SISS 2013). This distribution of water users is similar to that defined for the rest of the country by DGA (2012) (Fig. 5), and by the IPCC (2014a) at a global scale, according to which industrial processes and municipal applications use is about 20 and 10 % of the global water. However, the IPCC (2014b) foresees a significant growth of water withdrawals for energy and industrial processes, as well as municipal applications (10 %) over the next decades. Indeed, these water uses could exceed irrigation as the primary water user by 2050. Unfortunately, if this transition takes place in the basin, many users will be severely affected as they do not have water rights nor will have the means to purchase them (Bauer 1998; Reyes 2009).

Currently, LSCC can satisfy all the water demands and thus is not facing any water shortage. However, the groundwater table of El Culebrón-Lagunillas aquifer is indeed decreasing. Figure 6 shows the evolution of the water table of the Culebrón-Lagunillas aquifer

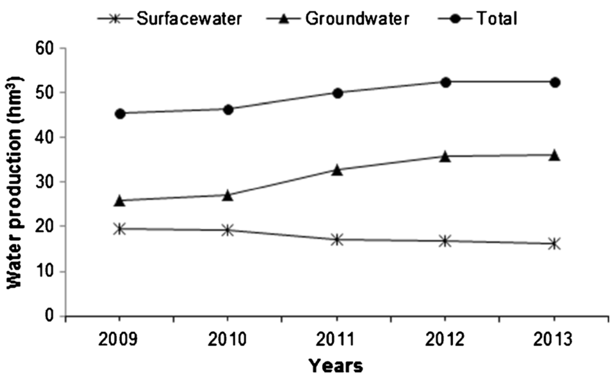

Fig. 4 Total annual water production by its source in the Region IV of Chile. Data from SISS 2013)

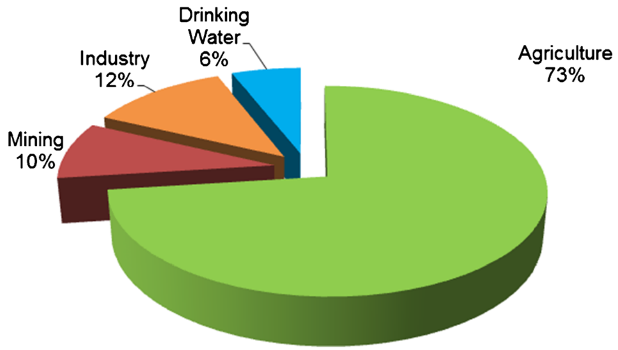

Fig. 5 Distribution of consumptive water uses in Chile (DGA 2012)

between years 1995 and 2014. Water level has significantly decreased (Mann–Kendall test $p \leq 0{,}1$), with a Sen's slope estimate of −1,3 m year^{-1}. Thus, the rates of growth and water demand in the future are not expected to be sustainable over time (ANDESS 2014). This depletion of groundwater is similar to that observed in other arid areas of the world (Durfor and Becker 1964; Jacobs and Holway 2004; Konikow and Kendy 2005). According to McGuire et al. (2003), in the over areas of the High Plains aquifer in the USA, farmers began extensive use of ground water for irrigation in the 1940's. The rapid increase of irrigated area from 8.500 km^2 in 1949 to 56.251 km^2 in 1997 resulted in a substantial decrease in portions of the aquifer. Suárez et al. (2014) also reported the same problem in the Copiapó River Basin, located 300 km north from LSCC area.

GRC (2013) modeled the water balance of the El Culebrón-Lagunillas aquifer on a scenario from 2004 to 2032 where they obtained a steady decline in the volume of the water stored in the aquifer until exhausted. This behavior reflects the absence of a recharge, because it does not have any major drainage channel and therefore the aquifer does not benefit from the extreme hydro meteorological events for recharging. The percolation of irrigation does not supply the demand. This modeling also considers a higher percentage of the water used for irrigation and an increase in the exploitation of drinking water, according to the population growth. This aquifer water balance showed a deficit of 283 L s^{-1} in a scenario of 22 years (GRC 2013).

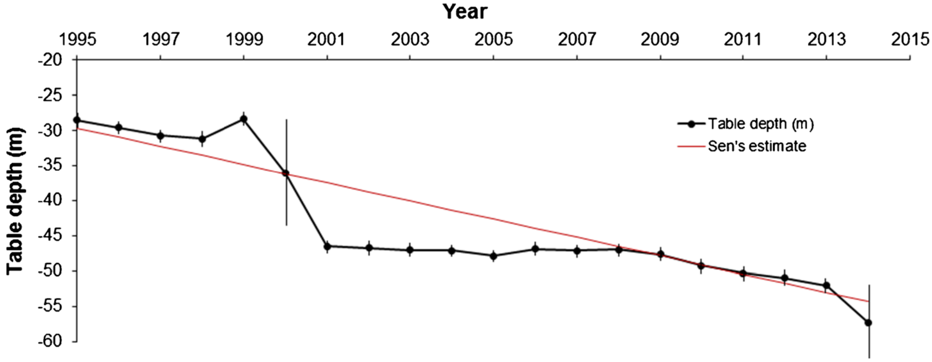

Fig. 6 Mean annual (±SD) water table level and trend analysis of the Culebrón-Lagunillas aquifer between the years 1995 and 2014. Data from DGA database

Critical natural resources, like water in LSCC, have a finite capacity of generation and regeneration. This is essential to the sustainability and one of the key concepts to be considered in urban planning, because all of our activities ultimately depend on nature. With fewer resources, cities in the developing world will require such a framework, so they can develop within the biophysical constraints imposed by nature (Baker et al. 2004).

The strategic importance of ground water for global water and food security will probably intensify under climate change (Taylor et al. 2013). Sustainable development in LSCC requires a balance between rural areas and the city itself, even more when the different water users compete each other for the water resources of El Culebrón-Lagunillas aquifer. An important fact to be considered at this point is that a great part of the use of water of the El Culebrón-Lagunillas aquifer, is for the irrigation of LSCC periurban areas. This is an important issue, because irrigation helps in stopping the land degradation in the periurban areas of the arid lands (Salinas and Mendieta 2013a). That is why it is so important to ensure the water of El Culebrón-Lagunillas aquifer: on one hand, there is a function of stopping land degradation through irrigation, and on the other hand, there is a function of ensuring the water security of LSCC.

The demand for drinking water comes from the inhabitants of the LSCC; in this respect, it is important to avoid the additional pressure on water and other critical resources of the cities, such as energy and soil. Rural areas being absorbed into the cities leads to an increasing competition over scarce water because of the industry and domestic use, farm houses, and recreation parks (Arha et al. 2014).

Cities are particularly vulnerable to water scarcity because their populations are highly concentrated and they require reliable supplies of water to allow the human and economic activities. Even temporary interruptions of the water supply can affect millions of people and the economic production. The long-term disruptions may be irremediable for the growth prospects of a city. Adaptation to water scarcity requires a range of solutions, including economic incentives, regulatory measures, and technology.

From an environmental point of view, the environmental risk of water scarcity is a major problem due to the fragility of the arid land ecosystems. Under normal hydrologic conditions, humans may adapt themselves to gradual environmental degradation but if the resilience of the system declines, the system becomes more vulnerable to disturbances such as severe droughts (Baker et al. 2004).

4 Conclusions and perspectives

Ground water plays a central part in sustaining ecosystems and enabling human adaptation to climate variability and change (Taylor et al. 2013). In this paper, we have highlighted the problem of water security for the sustainability of the LSCC and its dependence on groundwater resources. In a few years and without the implementation of adaptation strategies, this urban area could face a general water scarcity problem if the drought conditions remain unchanged and if the water demand trend continues its increasing.

Usually in practice, most water authorities choose to implement water restriction policies during drought periods (Mansur and Olmstead 2012; Sahin et al. 2015). However, these strategies are not sufficiently efficient by themselves (Sahin et al. 2015; Kahil et al. 2015). As seeing in Table 1, worldwide, the proposed mitigation and adaptation strategies for water

Table 1 Summary of different proposals in water security and adaptation strategies in other regions/cities around the globe

Region/city	Main proposed strategies on water security and adaptation	Reference
Sadah basin, Sana'a basin and Aden city, Yemen	Implementation of a combination of multiple targeted strategies including stakeholder identified strategies	Haidera et al. (2011)
British Columbia, Canada	Stakeholder participation, scale, multivariate analyses, and governance tools based strategies	Norman et al. (2013)
11 cities in the United States	Price-based approaches to regulate water demand	Mansur and Olmstead (2012)
Darkhan city, Mongolia	Integrated water resources management	Grit et al. (2015)
Bangalore city, India	Wastewater treatment and reuse and urban water recycling	Jamwal et al. (2014)
Valencia irrigation system, Spain	Integrated use of surface, ground and recycled waste water	Ortega-Reig et al. (2014)
Yulin city, China	Water demand management	Xiao-jun et al. (2014)
Albufera, Spain	Agricultural, urban and environmental market-based allocation of water during droughts	Kahil et al. (2015)
Queensland, Australia	Price-based approaches to regulate water demand	Sahin et al. (2015)

security cover a wide range of measures depending on the environmental, climatic, and socioeconomic characteristics of each region.

In this respect, the proposed strategies described in Table 1 range from the proposal of a basic integrated water resource management, which consider the construction of wastewater treatment plants (WWTP) in central Asia (Grit et al. 2015), to the proposal of the price and market based on approaches to regulate water demand in drought periods in the USA, Europe, and Australia (Mansur and Olmstead 2012; Kahil et al. 2015; Sahin et al. 2015). Among these strategies we can find proposals which consider the integrated use of surface, ground and recycled waste water for irrigation in regions where the agriculture is a mayor economic activity; as an example of this, we can mention the agricultural system in Valencia, Spain (Ortega-Reig et al. 2014). Other proposals consider the management of water demand in China (Xiao-jun et al. 2014). Some other strategies are based on stakeholder participation, scale, multivariate analyses, and governance tools in Canada (Norman et al. 2013), among others.

The analysis carried out by Haidera et al. (2011) in Yemen suggested that the implementation of any single adaptation strategy will not fully reverse nor will stop further declines in the water resources over the next decades. We believe that a combination of different strategies, together with a stakeholder participation, would be the best option for cities or regions marked by a combination of different territorial and socioeconomic characteristics. This is the case of LSCC which is characterized by an increasing aridity, a fast-growing urban development and a socioeconomic dependence in sectors that have a high water demand, such as tourism, agriculture, and mining operations.

The adaptation of rapidly growing urban areas to the climate change and the water scarcity involves a comprehensive territorial planning, which should include both the urban and the periurban areas and the current and the future availability of natural resources such as water. In this respect, it is essential, on one hand, to invest in water saving measures and also to ensure the water supply for the population through concrete actions. These actions could consider the capture of water coming from fog, the recharging of the aquifer with water from other basins and the construction of dams and desalination plants.

While desalination options may have a higher investment cost than some other rain-dependent schemes, they provide a greater degree of water security to a region (Sahin et al. 2015). In this respect, water desalination is an indispensable industry for large areas of the globe, such as most of the Arab countries (El-Sadek 2010). In other areas, such as the southern Spain, the desalination plants are integrated into the grid of water supply sources together with the reuse of WWTP effluent waters (Downward and Taylor 2007). In this region, desalinated water is even being used for high-tech and high-value agriculture (Qadir et al. 2007).

It is important to avoid the urban overpopulation. The promotion of technical irrigation in arid regions is critical for the raise of the producers' income and for the benefit of the rural population quality of life (Salinas and Mendieta 2013c). In this respect, the integrated water resources management at the river basin scale plays a key role on the sustainable land use planning.

The investment on specific programs to avoid land abandonment of marginal rural areas, is critical to reinforce the employment, the socioeconomic development, and the environment in general of the rural land in order to avoid migration to the cities and its further overpopulation (Salinas and Mendieta 2013b).

As the El Culebrón-Lagunillas aquifer is located at the coast, another environmental concern that must be further studied, is the future evolution of the saltwater/freshwater interface of this aquifer. This interface will be affected not only by future groundwater pumping, but also by climate change through changes in the groundwater recharge and the sea level. Some actions should be eventually implemented in the long term to avoid or to control saltwater intrusion to the aquifer.

Acknowledgments This work was funded by the CONICYT/FONDAP 15110020 Center. Authors also acknowledge the funding from the European Union (EU) Seventh Framework Programme (FP7/2007-2013) under grant agreement no. 283025 to Project COROADO. Thanks also to anonymous reviewers for their helpful comments and suggestions and to Ximena Santo for her valuable help in reviewing the language of the manuscript.

Conflict of Interests The authors declare that they have no conflict of interests.

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