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Water markets and social–ecological resilience to water stress in the context of climate change: an analysis of the Limarí Basin, Chile

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Abstract

The paper proposes an analysis of the social–ecological resilience of the Limarí Basin, an agriculture-intensive dryland in the north of Chile, featuring one of the most innovative market-based water managements and the most active water rights market in the country, but concurrently affected by an ongoing water stress situation. The Chilean water market, one of the main examples of the application of neoliberal policies in water management, has received mixed appraisals although, at present, few empirical studies evaluate the social and environmental conditions associated with their operation. This paper, on the contrary, maintains the necessity to assess the capacity of market-based models to face situations of water stress, particularly since mega-drought phenomena are projected to become a recurring and increasing problem during the following decades because of climate change. The study offers a mixed bottom-up and top-down qualitative empirical analysis of how the Chilean water market operates, providing relevant insights into four dimensions of the social–ecological resilience of the watershed: redundancy, diversity and flexibility; connectivity, collaboration and collective action; social–ecological memory and learning; self-organization and governance of system changes. The conclusion is that water scarcity is self-produced: despite the flexibility provided by market-based water management, the combined effect of strong deregulation, of the absence of territorial planning and integrated management of water resources, and of short-term attitudes and generalized mistrust, has led the system to the critical situation it is now facing.

Keywords Social–ecological resilience · Water stress · Water markets · Chilean water code · Climate change · Water governance

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1 Introduction

Due to its geographical, climatic, and productive characteristics, Chile is considered highly vulnerable to climate change (CEPAL/BID 2010; Ministerio del Medio Ambiente 2016). Water resources are particularly sensitive because of the extreme harshness, frequency, duration, and significance of the "mega-drought" or "aridization" phenomena affecting the country in the last years and expected to become a recurring and increasing problem during the following decades (Boisier et al. 2016; CR2 2015; Núñez et al. 2013a).

Reduction of up to 50% in stream flows and decreased seasonal variability are projected for most basins in the country (Vargas 2012; Ministerio del Medio Ambiente 2016) and changing temperature regimes will tend to rise irrigation needs (CONAMA 2008; CEPAL 2009) increasing pressure on the already highly demanded hydrological resources (Aitken et al. 2016). Climate effects are latitude-dependent with major changes for watersheds located at smaller latitudes (Núñez et al. 2013b) particularly affecting the agriculture-intensive drylands located in the northern part of the country. Water resources there—including underground ones—are already undergoing over-exploitation (Meza et al. 2015), and thus farmers must endure strong competitions for water access because of the mining activity (Delgado et al. 2015). As a result, such drylands are expected to suffer growing water shortages, and there will be pressure on local institutions and management to ensure a more sustainable and fair governance of water supply (Hadjigeorgalis 2004; Gentes 2007; Leon 2008).

Given such conditions, it is increasingly relevant to understand how local system cope with and adapt to present and future water stress as well as whether different kinds of water governance structures influence this situation positively or negatively. In order to make progress in such understanding, this paper puts forward a mixed top-down and bottom-up approach for the study of resilience to water stress of the socioecological system corresponding to the Limarí Basin (an agricultural-intensive dryland in the northern part of Chile) paying special attention to the role of the Chilean water governance system.

In recent years, a number of studies have targeted water governance in Chile (see Sect. 2), mostly borrowing tools from economics and/or from the study of legal institutions, and thus adopting what has been called a "top-down" approach. Little research has provided a thorough reflection and analysis on this issue from the point of view of water-stress-affected users, organizations and/or communities living in specific territories, i.e., from a bottom-up approach. This paper aims to complement this growing body of knowledge by introducing three main innovations: first, combining a top-down and a bottom-up approach to leverage and complement respective edges on the issue; secondly, focusing on social–ecological resilience rather than on exposition or vulnerability which, as argued below, allows for a better representation of specific risk dynamics, adaptation, and self-transformation of the local social–ecological system; thirdly, framing the said resilience not exclusively in terms of climate change, but rather looking at climate trends and changes as only some of the variables at work from the point of view of water users and organizations.

We hope this analysis will contribute both to the international debate on market-based water governance models and to a deeper comprehension of the conditions they establish to reduce or increase resilience of water-scarce environments and people living in them within the context of climate change.

After this Sect. 1, the paper goes on as follows: First, we are to discuss the existing literature on water governance systems in the country (Sect. 2); following, we are to introduce the conceptual and methodological framework for the study providing a brief description of the case study (Sect. 3); afterward, we are to present the main results from the study (Sect. 4); and finally, we are to close with a discussion, some conclusions and key insights (Sect. 5).

2 Water governance in Chile

Under the so-called water market, water resources access in Chile is treated as a commodity delivered to a free market regime which regulates the use through free interchange of "water rights" divided in consumptive (e.g., irrigation) and non-consumptive (mainly hydropower). In some basins in the country, Limarí being the most important one, a spot market was also implemented allowing for the direct sale and purchase of water volumes.

The model has been the object of a still unresolved and strongly polarized debate since its formalization in the Water Code (*Código de Aguas*) enacted in 1981 by the military regime.

As one of the main applications of neoliberal policy in hydrological management, the Chilean model has been replicated in other countries in the region (Galaz 2004) and has sometimes been highlighted as a reference point for water governance (Haughton 2002). Among proponents, the market model is praised for the potential in flexibility terms fostering investment and achieving optimal market allocation improving efficiency in the use of water and, supposedly, better addressing water scarcity issues and droughts (Molinos-Senante et al. 2016). It also allows for the use of water where water resources were already allocated, a common situation in the north of Chile (World Bank 2011). While some issues were identified with the initial allocation of water rights and in distortions associated with speculation and accumulation of "idle water" (Donoso 2003), most of these problems would have been solved by the 2005 Water Reform (Law No. 20.017) that strengthened and revitalized the water market and the following 2006, 2008, and 2010 reforms[1] which, respectively, modified the regulation on the exploitation of groundwater, improved the operation of water reservoirs, and created the Ministry of Environment (Nauditt et al. 2010). The market-continuing expansion, both geographically and volumetrically, is quoted as proof of the ability to meet users' needs although it is conceded that some issues do remain such as imperfect registering of water-use rights and transactions, growing conflicts for water usage, and the lack of sufficient coordination and articulation between government institutions and information on groundwater resources (Hearne and Donoso 2014; Valdés-pineda et al. 2014).

The relative fragmentation of water-related institutions and the lack of clear and consistent policy and planning for the sector appear among the most-agreed upon challenges for the model (World Bank 2013) implying difficulties in water governance, especially when considering the increasing frequency and intensity of extreme climate events (Clarvis and Allan 2014) often impairing the possibility of achieving a sustainable and equitative use of resources, particularly affecting subsistence farming (Delgado et al. 2015) tending to produce a growing concentration in water rights ownership. The sector is generally considered lowly regulated (Bauer 2010) and existing norms are sometimes poorly implemented while water rights are not always properly exercised or guaranteed (Vergara 2015). Moreover, the

[1] Respectively, Laws No. 20.099, 20.304 and 20.417. To access the full text of any of the norms mentioned here: https://www.leychile.cl/.

very same regulations are applied throughout the highly diverse contexts of the country implying frequent collision of interests and visions around water resources that give way to heated conflicts (Rivera et al. 2016; Costumero et al. 2017) difficult to solve within the current legal framework. These conflicts often call into question the superimposition of the productive value of water over social and environmental uses (Retamal et al. 2012). These would prevent the system from prioritizing among different water uses tending to generate increasing pressures over the use of water directly affecting ecological flows (Bauer 2015).

Therefore, the model has been deemed incapable of supporting a sustainable water resource management (Retamal et al. 2013) and, in fact, the deployment of new irrigation infrastructure by inducing an enhanced growth in cultivations sometimes may have increased—rather than reduced—exposure to water stress (Vicuña et al. 2014). This situation is worsening considering the current climate trends: In the most pessimistic scenario, the available hydrological resources may be insufficient to cover the existing water rights during almost half of future years (Meza et al. 2012). This raises urgent calls toward adaptation and part of this involves infrastructural arrangements such as irrigations dams. Nevertheless, these should be complemented with integrated watershed governance (Oyarzún and Oyarzún 2011) and a more informed and active resource management on the part of water users (Vicuña et al. 2012).

Unfortunately, even though climate change is increasingly recognized by Chilean farmers, the incorporation of adaptive practices has been slow and limited, mainly focusing in the short-term and on the simplest, most accessible strategies (FAO 2010). Adoption of these practices negatively correlates with poverty and as a result, they tend to increase inequality (Jara-Rojas et al. 2012); similarly, although paying for water rights might produce incentives for water savings, it also generates regressive distributional effects and may induce more well-to-do farmers to stock on water not only for speculative reasons, but also as a risk-mitigation strategy (Arnold et al. 2015). Education and access to relevant and updated information play an important role in improving adaptation; there are significant differences between what experts and farmers consider as the most suitable adaptation practices though (Roco et al. 2014, 2015, 2016) and a significant part of the population believes that ultimately, the responsibility to respond to climate change should fall on the government, the scientific community and international organizations (Rojas 2013). On the other hand, mainstream discourse—particularly among government institutions—connects adaptation with the modernization of agricultural systems, and some have highlighted a positive effect of traditional knowledge and practices on both socioecological resilience and agro-biodiversity (Montalba et al. 2013, 2015). Moreover, it has been noted that adaptation to climate change should not be separated from the development trajectories that shape actors access to social, economic, political and natural capitals, something usually understood as “double expositions” (Montaña et al. 2016). In the case of Chile, inequality between farmers appears to be particularly large, and it should therefore be a core aspect to focus on. In fact, communities may assess climate change as one more challenge in the context of other transformations, and their adaptation will depend on both their level of understanding/awareness of the phenomenon and on complex sociocultural factors as their proactive–reactive attitude to change in general, institutional capabilities, social organization and so on. (Young et al. 2009).

This is in line with what is increasingly noticed in other fields of climate and global environmental change, vulnerability, and adaptation showing the understanding of how people and groups respond to climate change requires more complex frameworks toward their capabilities and perceptions (Qin et al. 2015). That is to say, to adopt new theoretical and methodological models that overcome traditional society–nature and scientific–traditional knowledge boundaries toward a more complex and multi-level understanding of social–ecological relationships and dynamics (Rojas 2016), in other words, to think about it in terms of social–ecological systems and social–ecological resilience. This will be further explained in the next section.

3 Theoretical framework and methods

3.1 Resilience in social–ecological systems

During the last decades, the concept of resilience has been the object of rapid growing attention for a variety of disciplines (Bodin and Wiman 2004). While it is sometimes used figuratively as a synonym of sustainability (Christmann et al. 2012), resilience should be more precisely considered as the degree to which affectations or modifications in the structure of a system can be triggered by external or internal disturbances (Gallopin 2006) whether they are social or environmental ones or a coupled social–environmental ones). However, resilience is neither merely the exposure to an external threat nor just the opposite of its vulnerability (Urquiza and Cadenas 2015). It rather refers to the ability of absorbing disturbances in the surroundings combining change with the preservation of the relationships between its components (Holling 1973); that is, it is able to modify variable elements while keeping its basic structure (Gunderson and Holling 2002), identity and "basins of attraction" (Walker et al. 2004). However, since complex adaptive systems present multiple regimes of stability, it may also refer to the system ability to change rapidly and seamlessly from one regime of stability to another (Gotts 2007). A contemporary definition of social–ecological resilience acknowledges it as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedback, and therefore identity" (Folke 2016) which encompasses both adaptability (actions that sustain development on current pathways) and transformability (shifting pathways or creating new ones).

As such, thinking about it in terms of resilience rather than exposition or vulnerability may help to better describe joint social and ecological states and development trajectories, identifying critical thresholds, facilitators, and barriers for the transition between different states and trajectories (Sietz and Feola 2016); to discover complex and sometimes latent ways in which agricultural practices can maintain or improve social communities and their environments (Ifejika 2013); to explore how agricultural drought management strategies may evolve over time through continuous learning (Rey et al. 2017); or to highlight the potential for local organizations and people taking charge of their own adaptation where the broader context proves ineffective (Doughty 2016).

Based on the existing literature, the concept of social–ecological resilience can be broken down into four key dimensions (Fig. 1):

1. Redundancy, diversity and flexibility (shortened as flexibility in what follows) refer to the system self-sufficiency and the variety of tools (institutional, technological, productive or biological ones) it can activate when there is uncertainty or shock, thus expanding its array of possible responses to the changes and disturbances it faces (Tompkins and Adger 2004). Internal diversity, and thus, flexibility, can tend to improve when the system capacity for innovation and self-transformation is high (Cumming 2011).

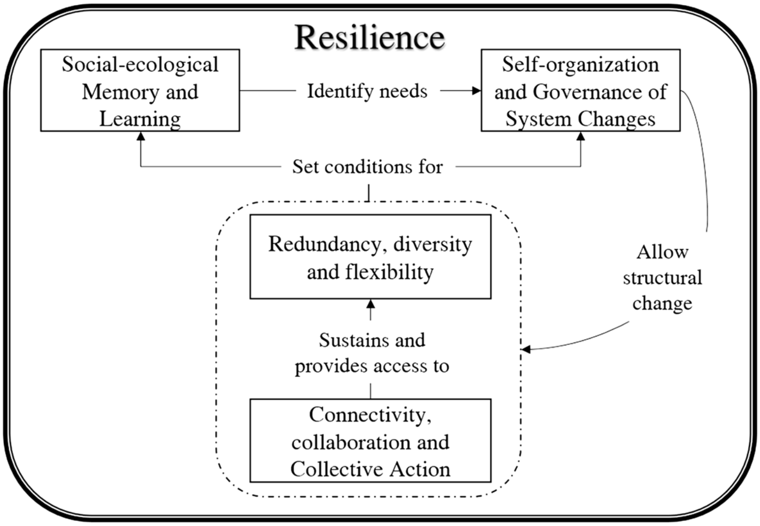

Fig. 1 Resilience in social–ecological systems. Compiled by authors

2. Connectivity, collaboration, and collective action (shortened as connectivity) refer to creating opportunities for interaction and thus greater diversity of social and ecological resources (Olsson et al. 2004), enhancing access to resources and the possibility of modifying regulations or institutions for them to be more in line with local conditions (Tompkins and Adger 2004; Folke et al. 2005) and in doing so guaranteeing a more sustainable, equitable access to natural resources, calling for joint work, support networks, participation in decision-making and polycentric modes of governance (Ostrom 1990, 2009).
3. Social–ecological memory and learning (shortened as memory and learning) refer to bringing together all the knowledge of a social system about its environment, how this has been impacted by changes in the surroundings, and which adaptation strategies have been developed (Folke et al. 2005; Olsson et al. 2006), discussing and incorporating both formal and informal—scientific and popular—knowledge in decision-making (Saterfiel et al. 2013) and making it available to the community at large, thus fostering shared learning, i.e., potential to reformulate or incorporate new knowledge over time (Nykvist 2012). Greater connectivity allows for additional levels of knowledge and social–ecological memory while making an increased collective learning possible during change processes.
4. Self-organization and governance of system changes (shortened as self-organization) refer to including efficacy in both preserving the system original identity and driving any transformations needed in order to reach more desirable states in the face of threats or when the system original condition is deemed unsatisfactory (Folke 2006; Engle 2011), and also effectively dealing with any conflicts associated with such changes (Folke et al. 2005). This capacity is strongly dependent on the three dimensions discussed above since it requires the system to be able to access and modify a wide variety of elements and relationships, activate its networks to transfer knowledge and resources where needed, and draw from past experiences and learning's to make innovations and respond to emerging situations.

Such dimensions may be regarded as "predictive" indicators of social–ecological system resilience. Since resilience is an intrinsically emergent property (Walker and Salt 2006), it may not be fully assessed without looking at its effects on some other relevant variables (for example, the continuity of business, of local livelihoods, of a species and others). This is not the approach we are following here. On the contrary, by breaking down resilience into its fundamental determinants, we are focusing on how the market-based water governance system used in Chile is fostering or hampering the social–ecological resilience of the Limarí Basin. Such an approach may be used to either compare different forms of water governance within similar areas assessing their relative impact on the determinants of social–ecological resilience on such areas or to compare the suitability of the same form of water governance in different areas assessing the degree to which area-specific features condition the impact of such form of water governance on the local social–ecological resilience. However, since our proposed method does not actually look at the *effect* of social–ecological resilience itself, it may not be the best approach to compare how such resilience may be changing over time within the same system—although looking at changes in its determinants may provide us with some outlook or trend regarding such changes. A factual assessment of the degree of socioecological resilience of water basins in Chile would require a different framework which in fact is the object of an upcoming paper built over this one.

3.2 The case: Limarí Valley

As anticipated, the proposed framework was applied to the case study of the Limarí Basin, an agricultural-intensive dryland located 600 km to the north of Chile's capital in the IV Region (Región de Coquimbo), in a semiarid region showing a significant inter-annual variability in precipitation and streamflow (Favier et al. 2009; Strauch et al. 2009). Dry periods are common and generally associated with the cold phase of El Niño Southern Oscillation (Karoly 1989; Meza 2013) and the Pacific Decadal Oscillation (Mantua and Hare 2002). As it is common in the region, Limari's hydrology is dominated by highly irregular snowmelt and scarce precipitation meaning that water for irrigation is only available during spring and summer and with extremely streamflow uncertainty, implying an ever-persisting risk of water shortages (Vicuña et al. 2014).

Also because of this reason, the valley stages one of the most innovative market-based water governance and the most active water rights market in the country featuring both permanent and temporary water rights transactions (water rights market) and an electronic water market for water volumes real-time interchange throughout the watershed (spot market). Figure 2 depicts the valley with its main water infrastructure: red dots indicate wells, blue squares are State-built dams, white triangles are minor dams, and black triangles and green diamonds represent future dams (currently under study).

The core of this infrastructure is the so-called Paloma System, a network of three dams and multiple interconnected irrigation channels allowing for water storing and distribution. With no equal in Chile, the system acts as a "water bank" regulating access to water resources (highly valued and competed for in the region due to scarcity) among nine user organizations through an innovative operational system managing volumes stored in the 3 dams allowing users to exchange rights and deposits and to even make water withdrawals or loans, as it would happen in a real bank (Donoso 2003; Hadjigeorgalis 2004; Fuster 2006; Díaz 2008). This creates favorable conditions for research since it allows us to observe the functioning of the Chilean water model where it is fully operative.

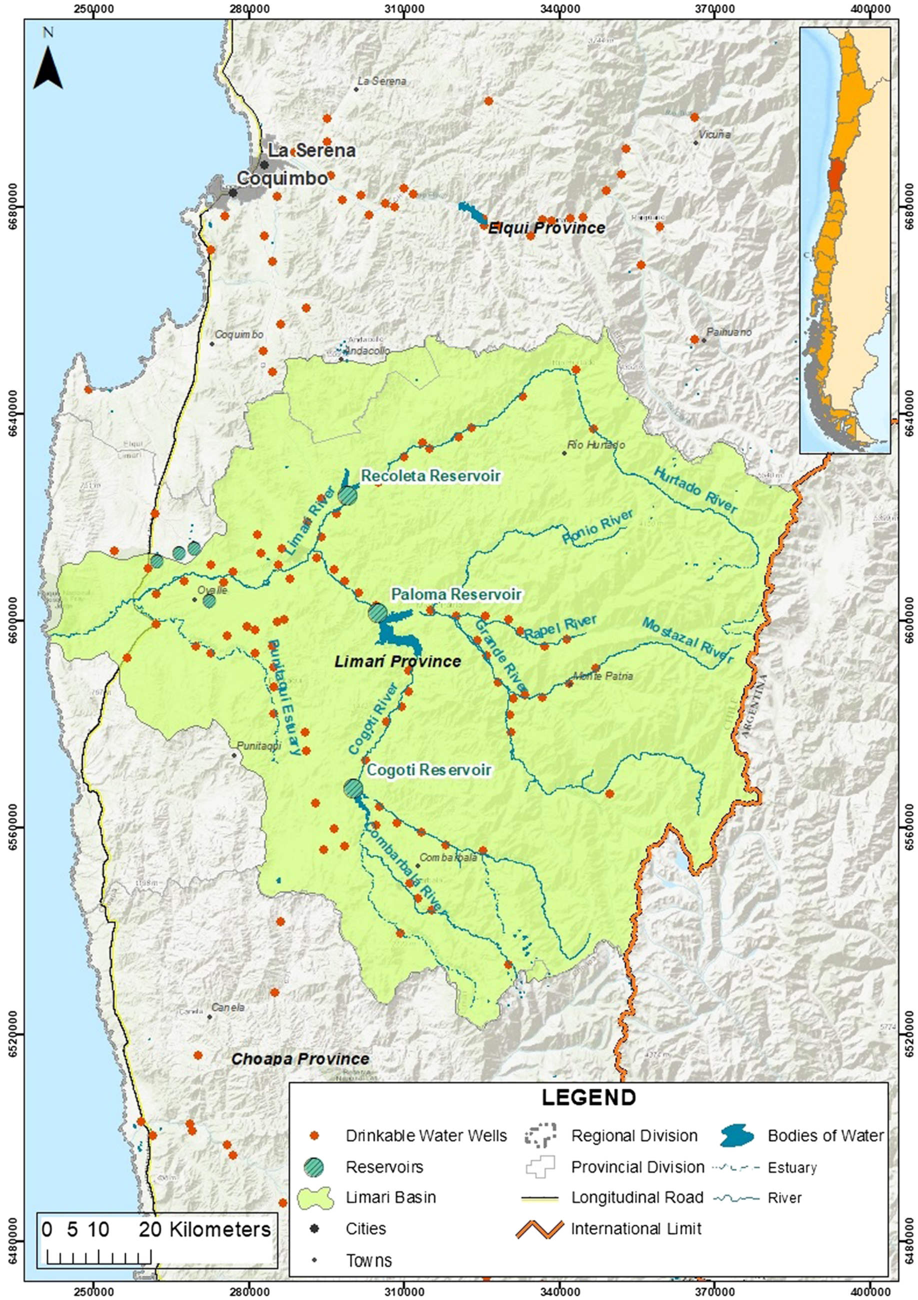

Fig. 2 Map of the Limarí Basin. Compiled by authors based on data from Chile’s Water Resources Directorate (*Dirección General de Aguas*): http://www.dga.cl/productosyservicios/mapas/Paginas/default.aspx

Thanks to this system and despite the harsh climate conditions, the valley was able to host an important and diverse production of fruit and vegetables—both temporary and permanent plantations. In recent years, there has been an accentuated replacement of often permanent traditional crops in favor of others which are more intensive in the use of labor displaying higher yields per hectare. However, agricultural yield has been systematically decreasing since a few years ago due to prolonged and heavy droughts. The field work was mostly done between 2013 and 2014, i.e., during the crisis worst years. Although 2016 and 2017 have seen a partial recovery in terms of water flow and agricultural productivity, climate projections indicate that water scarcity will be a recurring problem in the area making particularly important to analyze social–ecological resilience to water stress and, especially, to assess how the current water governance framework impacts on such resilience. In fact, due to the joint effect of hydrological instability and socioeconomical and productive conditions (namely, the low human development index, importance of agricultural production for the workforce and dependence on irrigation), the Limarí Basin has some of the highest agri-business vulnerability to climate change settlements in the country (Ferrando 2002; Peña et al. 2004).

3.3 Methodology

To understand how the Chilean water model interacts with the specific environmental, economic, social, institutional, organizational, and cultural conditions of the researched area, and also how it impacts on the capacity to absorb and manage water stress in a context of climate change, this paper proposes to understand the Limarí Basin as a social–ecological system whose resilience may be observed by operationalizing the four dimensions explained as follows:

- Within "flexibility", we aimed at understanding how the water market actually works providing "economic rules" for the allocation of water resources. We also aimed at observing the institutional and legislative framework in which such market operates (mainly the Water Code and its reforms and local user organizations' role).
- "Connectivity" assessed the collaboration degree between different actors of the socioecological system along the vertical and horizontal dimensions. The vertical one accounts for the influence of state organizations in the management of water resources and relationships between State, experts, and farmers from the area, whereas the horizontal one accounts for cooperative and/or competitive actions in the management of water resources and trust assessment and the impact on collaboration.
- "Memory and learning" was articulated as knowledge of the basin water situation and the ability to learn from previous drought episodes.
- Finally, "self-organization" included the capacity for innovation (developing new strategies) and self-transformation (modifying operational, organizational, legislative and/or institutional conditions) of the system to deal with increasing challenges in water resources management.

As previously stated, the present study combined a top-down and a bottom-up approach by comparing existing geographical, climatic and economic-institutional information as well as official documents regarding the water market with different stakeholder discourses regarding the water market performance in the local context.

To gather the latter, semi-structured interviews were conducted during two field trips lasting 3 months each (January–March 2013 and January–March 2014). Semi-structured interviews and qualitative methods in general have been deemed particularly appropriate to understand and explain perceptions, behaviors and decisions of different watershed actors and inhabitants regarding water issues and management by reconstructing the way these are understood, experienced, reproduced and signified within different socioeconomical, geographical, and cultural contexts (Retamal et al. 2011).

To select the informants, an information-oriented sampling strategy (Denzin and Lincoln 2011) was used aiming at identifying distinctions and evaluations made by different stakeholders and thus, ensuring the maximum possible diversity in terms of perspective. As a result, a total of 55 subjects structured by type were interviewed including:

- 6 experts on the topic at a national, regional and local level (two per level);
- 1 left-wing coalition representative that occupied political responsibility positions for the 2006–2010 government term and 1 right-wing representative active during the 2010–2014 term;
- 8 government officials from the DGA (*Dirección General de Aguas*: Water Resources Directorate), CNR (*Comisión Nacional de Riego*: National Irrigation Commission) DOH (*Dirección de Obras Hidráulicas*: Hydraulic Works Directorate) and PRODESAL (*Programa de Desarrollo Local*: Local Development Program);
- 6 market intermediaries (3 formal and 3 informal brokers);
- 9 active administrators and/or managers from different user organizations from the Paloma system;
- 2 local and 2 national ONG representatives;
- 20 farmers: 8 small ones, 5 medium ones, 3 large ones, and 4 active agricultural companies' administrators in the area.

Some of the farmers and government officials were interviewed twice (once per field trip) to appreciate the temporal perspective of their narration. The interviews followed a semi-flexible script covering a variety of topics ranging from the social conditions existing in the valley to the regulation and operation of the water market and the diverse strategies employed to face water stress as well as the cultural meanings and assessment respect to water and market operation.

The interviews were transcribed and subject to coding and analysis together with a selection of relevant secondary documents. Namely, official documents from the organizations involved in the water market—aiming at identifying elements that may allow to analyze resilience of the social–ecological system existing in the Limarí Basin and assessing the impact of the market-based water governance on such resilience. The qualitative analysis software *AtlasTi* was used to support the coding and interpreting of the data. The entire procedure was performed by only one coder (thus making it unnecessary to check for intercoder reliability) on the basis of a mixed set of codes, partly pre-defined on the basis of the existing literature—in accordance with the four analytical dimensions described above—and partly emerging from the empirical data itself. This was complemented with ethnographical observation providing insights into the functioning of the water market and of the user organizations as well as on the relationships between government agencies officials and user associations. More details on the interviewees, interviews topics, or the analytical categories used for the coding procedure are available on Online Resource 1.

Since this study adopted a qualitative approach, no answers and codes frequency or correlation analysis will be provided. Instead, we will narrate the complex web of sense-making through which the interviewed actors build their understanding about the water governance system and the effect it produces on the Limarí watershed resilience in the face of water stress. Because of length restrictions, we are not providing transcript quotes. Should the reader be interested, however, a sample collection is available on Online Resource 2.

4 Results

The field research allowed us to identify a variety of elements that are promoting or limiting each of the four dimensions of the social–ecological resilience identified in the conceptual framework as well as other aspects whose effect are more ambiguous. These results are summarized in Table 1 and will be briefly presented below organized according to their analytical dimension.

4.1 Flexibility

The separation enacted by the Water Code between property of land and water was originally quite well received especially by farmers since it reasserted what they had already been doing informally in the valley at least since the nineteenth century. Moreover, the new status the Code has given to water rights as private and transferable property appears to have brought great flexibility. It has also invigorated the market providing for a bigger number of rights available and the opportunity to transfer water from a more profitable source and improved security. Likewise, according to local sources, it has enhanced security for the investors in relation to the use of resources increasing therefore the chance for investment because of the lower risk.

The spot market was equally or even more important for enhancing water flexibility allowing for a large variety and efficiency of volume transactions mainly thanks to precise resource management carried out by the Paloma reservoirs and the important role played by user organizations (see below). The establishment of an electronic platform to support this market has increased market transparency while lowering transaction costs in providing an information source regularly accessed by many farmers, even though they themselves do not use it for trades. In fact, the actual trading on the electronic market is mainly limited to big companies that value the security offered by this legalized institution in comparison with traditional water stockbrokers and they can pay the fee to access the service.

Likewise, water volume trading within the spot market also faces barriers ranging from high prices of water, especially during droughts to cultural barriers and issues related to accessing information. The main water buyers are the largest agricultural companies which have both the resources and the strongest need since they have huge volumes of permanent crops to keep and export commitments to fulfill. Smaller farmers, particularly vegetable growers usually act as sellers: although the most traditional ones would not admit it—it is not well seen to earn money trading water—farmers do sell both water volumes and water rights on a regular basis because it is often more profitable to sell the seasonal water than to plant during a time of drought. Water rights can even be used as backup for mortgage requests and are usually referred to as economic or financial assets.

Due to limited State regulation, the impossibility to register new water rights—since more than 30 years ago when the basin was declared exhausted—and a constant increase in cultivation in the area, water prices have been systematically rising during the last decades

Table 1 Summarized results. Compiled by authors

Dimension	Promotes resilience	Ambiguous effect	Limits resilience	Overall effect
Flexibility	Separation water-land: old practice, and driver of flexibility and value Rights market fosters investment, spot market provides flexibility; electronic market lowers trading costs	Polarized attitude toward infrastructure investment and role of the State User organizations: key role in self-regulation but limited capacity for action and low legitimacy of decisions	High deregulation and ambiguous legal standing of water Unequal access to market, high and growing costs, concentration of property	Predominantly limiting resilience
Connectivity	User organizations: high professionalism and key role in irrigation efficiency and regulation of water transfers Long-standing relationship between regional management and user organizations Strong dam infrastructure: fosters the capacity to transfer water	Dying tradition of collaborative action (but persisting reliance on support networks)	Issues of leadership and participation in user organizations The trust issue and water theft Slow, inefficient and unclear procedures; new government, new policy	Ambiguous
Memory and learning	User organizations are learning	Traditional knowledge: ¿resource or trap? Traditional farmers are less prone to change but non-traditional farmers are less attentive-knowledgeable with respect to local ecological cycles Potential of collaboration between user organizations and experts (with room for improvement)	Serious gaps in knowledge and communication, especially within public institutions Communication difficulties between experts, State and private sector Weak learning entails low sustainability	Predominantly limiting resilience
Self-organization	Market and user organizations as a driver for innovation	Awareness of the need of a new and more sustainable legal framework is needed, but the Water Code is inflexible and difficult to change (as proved by the 2005 Reform)	Reactive attitude of State organizations Weak political leadership	Predominantly limiting resilience

making it ever harder for small- and medium-sized producers to keep their agriculture business. Many farmers stated they had to sell their shares to cope with financial difficulties and have not been able to recover their stocks and reestablish their wealth later on. Therefore, water resources ownership has become more and more concentrated and water is generally perceived as a symbol of wealth today.

Numerous critics ranging from entrepreneurs, lawyers, stockbrokers, experts to some members of civil society agree that under the current framework the market is highly deregulated and they emphasize the need for water rights trading and movement better supervision. This is worsened by the restrictive interpretation that State organizations' employees make of the legislation: Although the Code—rather ambiguously—differentiates between the *use* of water (privatized through the water rights) and its *property* (which should always remain the State´s) in practice, there is a strongly rooted tendency to consider it as a purely private resource.

The ability of State organizations to govern water resources accessing is widely questioned and private parties are mostly autonomous in carrying out economic trading with their stock and water volumes. This has become a heated subject of debate and opinions on the matter tending to be highly polarized around the chosen political stance: Right-wing representatives highlight the chances given by national regulation to grow private investment allowing the State to be free from constant spending on the issue and mainly regret the lack of sufficient investment in reservoir infrastructure and the scarce ability of local organizations to solve water-related conflicts which often times have to be brought on to court. Left-wing spokesmen, meanwhile, stress the Code deficiencies, the lack of public access to information and the narrow scope for State organizations to act and confront problems relating to water resources such as achieving a more sustainable water resources management and preventing exploitation spread and intensity.

In this context, the Limarí Basin user organizations have developed their own regulations to establish the limit and condition for water transfers. Although such regulations are mainly limited to the spot market, with scarce or no jurisdiction on the water rights market, they govern a large amount of the trading: In fact, even government officials consider the existence and proper functioning of the user organizations to be a key component for the reasonable administration of water resources. However, both entrepreneurs and large-scale farmers have heavily criticized conditions and regulations that these organizations impose on the market which would betray a lack of knowledge from leaders and administrators, hide unresolved conflicts of interests and ultimately, hinder the free market.

4.2 Connectivity

Apart from contributing to water market self-regulation, user organizations also play a key role in terms of associativity and connectivity within the basin allowing for a quick and efficient managing of water stock, overseeing the maintenance of infrastructure and watering systems, distributing the resources among the water rights holders, and enabling changes that can only be carried out at a community level such as building, maintaining and improving headworks, dams and canals. Most user organizations are highly professional, with hired, trained administrators and security guards. However, they tend to attract strong criticism for allegedly not acting in the interest of the whole community. This is partly because their share-based voting systems tend to favor larger farmers discouraging smaller ones from taking part of the meeting and generally lowering the legitimacy of decisions. However, it is also partly due to frequent accusations to administrators to be taking advantage of their positions for personal profit.

In general, mistrust is a common issue in all forms of organization and collaboration in the valley, and it tends to be mainly from small owners and directed toward those farmers or companies with a larger amount of water stock. In any case, the main cause of mistrust pervading the system is water theft, i.e., illegal water extraction, which is the object of constant suspicion and worry both among neighbors and user organizations. This produces conflicts that become especially critical at times of extreme scarcity when such actions occur more frequently and contemporarily, farmers' tolerance decreases.

Although the valley has a long-remembered tradition of communal activities, most of them have all but disappeared nowadays and collaboration tends to be limited within small groups of farmers with homogenous characteristics and a clear purpose. Among relatives, a persisting form of support network is water sharing, which is eased by the Paloma System allowing for water volumes to be interchanged even at large distances within the basin. In contrast, collaboration among neighbors usually occurs through the lending of machinery or workforce and sharing a part of the harvest for private consumption. Group water renting was quite spread too, before it was formally incorporated in the spot market.

Along the vertical dimension, user organizations and the regional government show a well-established and long-standing collaboration which is good when compared to other parts of the country although complaints were raised about the procedures being too slow particularly in times of scarcity, often unclear, and the inefficiency of some strongly advertised State-led initiatives such as cloud seeding. However, one of the most common sources of criticism relates to the tendency of every new government to discontinue and modify policy introduced by the previous administration to the extent of discontinuing programs and trainings halfway.

4.3 Memory and learning

The interviews pointed out to a general lack of information about water cycles, snow density, amount of water stored in reservoirs and even water rights since these are frequently registered in books stored in different country locations; particularly worrying is the widespread ignorance about the capacity of aquifers preventing users to think about groundwater as a common source.

State agencies (namely the DGA) show poor access to information, at times because of scarce interest and often because of not having enough resources, personnel and/or skills to make use of the knowledge obtained. There are additional gaps in information transferring from State and experts to user organizations and farmers often leaving plenty of room for interpretation preventing those from making informed decisions on the extent, intensity and type of crops which may be sustainable in the basin or to assess risks associated with an inadequate or unsustainable management of water resources.

Learning is also weak, particularly concerning local and regional authorities: measures implemented to tackle droughts tend to be reactive and stop when droughts end, even though these events tend to be cyclical in the region; moreover, no limits are set on farming exploitation, something that farmers themselves deem necessary to prevent excessive stress on water resources and the growing replacement of temporary crops with permanent crops requiring a continuous use of water. In fact, Paloma System administrators suggest the basin has already reached its hydrological limit and foresee strengthened risks for agricultural production. Unfortunately, the DGA believes the State has no room to enact new regulations relinquishing to “natural selection”: Those who have enough water rights will survive.

Some learning did occur within user organizations gradually setting up procedures, conditions and thresholds for water transfers trying to make them sensitive to the availability of water and the eventual effects they may produce on other water users. Moreover, there is good potential for cross-learning and information exchange between user organizations and some active research centers in the area; however, work is needed to make the research more intelligible for the average users and to engage State institutions in the process.

Traditional knowledge receives ambiguous appraisals: On the one hand, the lack of local knowledge has often impaired the decision of external companies concerning the purchase of sufficient amount of water shares for crops they were planting, making it even more worrisome that such knowledge is disappearing as traditional farmers grow old or retire. On the other hand, traditional knowledge has proved of little use when unexpected seasonal changes occurred, partly as a product of climate change. In such cases, the largest producers were shielded because they have access to professional advice and forecasts whereas small traditional farmers incurred in significant losses. They often chose to rely on their preconceived beliefs rather than on user organizations official announcements. Moreover, the eldest farmers’ refusal to invest in machines has limited their income even in the best years. However, their farming activities have been made more ecologically sustainable than the intensive and/or industrial agriculture at the same time.

4.4 Self-organization

Most innovation comes from the market—one example is the electronic spot market, which in the future may even allow to transfer water from the rainy South to the dry North—and from user organizations, the latter being mainly focused on improving efficiency and regulating transfers. Attempts at a more integrated, multi-stakeholder watershed management have been made but they were hampered because of the lack of a suitable legal framework and the political instability connected to the change of government. Farmers tend to be more short-term-oriented concerned as they are with saving each year’s harvest.

State organizations show the lowest innovative skills tending to prioritize measures directed to mitigate emergencies and avoid collapse leaving few resources available to address broader issues; in part, this seems to be due to a narrow political focus on the next elections disregarding longer-term commitments. On the other hand, the very market model makes it hard for public institutions to implement changes since it would require a huge amount of resources for them to purchase water rights needed to boost actions for safeguarding sustainable basins.

Most felt priority concerns the regulation of crops and seeding: Even large agricultural companies are aware that free competition is incompatible with ecological homeostasis in the basin and most respondents highlight the need to implement a more integrated water governance.

From this perspective, the 2005 Water Code reform—itself the result of a very long and laborious process—is accused to have been unable to tackle or even to have extremized the fundamental market orientation of the water model: Some of the amendments aimed at reducing the concentration of property and stimulating the market proved quite ineffective and seemed to promote the intensive use of aquifers, thus appearing as more appropriate for contexts of high abundance than for ones involving scarcity. The implementation of an ecological flow, although initially well received, only applies to rivers with available rights and it is therefore useless for high-demand areas such as the Limarí Basin where water flows are already exhausted. Conversely, one of the most controversial elements refers to lack of restrictions on the change of water rights use, a faculty commonly used to switch water from agriculture to the more profitable mining in the north.

In the end, while there is increasing awareness of water resources efficient management importance, most of the attention still goes toward the economic dimension while environmental issues have been indefinitely postponed with unforeseeable consequences.

5 Discussion and conclusions

The research presented here has allowed us to distinguish those processes and conditions that foster, reduce, or ambiguously affect the social–ecological resilience to water stress of a dryland such as the Limarí Basin and to clarify potentials and limits of market-based water governance models on said resilience, particularly considering the new challenges arising from climate change and expected effects on hydrological resources.

Based on the results presented above and summarized in Table 1, we can conclude that overall the market-based water management system is hampering rather than fostering the Limarí Basin socioecological resilience.

This seems to be particularly the case regarding the memory and learning, and self-organization dimensions. In the first case, the main determinants are a deficient knowledge management and transfer on the part of State organizations and the farmers' biased understanding of hydrological and climatic processes while traditional knowledge seems to be playing a more ambiguous role somewhat improving ecological sustainability, and at the same time impairing farmers' ability to respond to a changing climate. In the second case, resilience is also hampered by the short-term attitude of both farmers' and State organizations—limiting their attention toward deeper and more longer-term processes such as mega-drought and other climate change-related phenomena—and the low empowerment of local actors to enact the deep changes that would be needed in the legal-institutional framework, while public institutions lack resources, knowledge and political will to help with these initiatives. Thus most innovation potential seems to reside in the very market.

In the Flexibility and Connectivity dimensions, water management impact on resilience is more ambiguous: however, referring to the former, results seem to show that flexibility is currently declining with a negative outlook in terms of resilience. While the water market does provide users with some increased Flexibility in addressing their water needs in the face of scarce resources, the unequal access to such markets, the constant rise in prices and water concentration tend to aggravate the situation for the poorest—and most traditional—farmers. Moreover, flexibility is also hampered because of the lack of State regulation and overuse of the spot market to plant more than each farmer is able to handle only by making use of the rights he owns, and often inducing to substitute temporary crops for more permanent ones, thus renouncing to the "buffering" capacity the former offered with respect to water scarcity: innovation seems to be leading to a more "efficient" but ultimately less flexible and sustainable use of the resource. Considering the increasing and long-lasting water stress the region will have to face, this represents critical risk for social–ecological system resilience.

With respect to connectivity, user organizations showed a strong potential which was, however, deeply hampered by the unfair and, ultimately, illegitimate decision-making mechanisms these organizations adopt and the general mistrust reigning in the system leading to frequent and often poorly managed conflicts. In the vertical dimension, although there have been some efforts toward collaboration, these are often inefficient and highly dependent on political trends.

Although some of these results may be specific to the Limarí Basin, many of them confirm previous research on other areas. This allows us to have a more general overview of the Chilean market-based water governance framework. Various trends hampering resilience shown in the case were found to be quite a recurring feature of water markets in Chile: that is the case with the tendency of such markets featuring unequal access and concentration of property (Arnold et al. 2015; Delgado et al. 2015; Jara-Rojas et al. 2012), inducing an under-valuation of non-economic uses of water (Prieto 2016) and providing incentives to the over-exploitation of existing water resources and the increased reliance on permanent crops (Bauer 2015; Montalba et al. 2015; Retamal et al. 2012; Vicuña et al. 2014). Especially when coupled, as it often seems to be the case in the country, with limited administrative supervision and poor vertical as well as horizontal coordination (Retamal et al. 2013; Valdés-Pineda et al. 2014; Montaña et al. 2016), such conditions have been shown to lead to increasing conflicts relating to the use and allocation of hydrological resources (Bauer 2015; Frêne et al. 2014; INDH 2016; Rivera et al. 2016; Costumero et al. 2017), and at the same time limiting the collective decision-making a must for an integrated management of such resources and the protection of freshwater and terrestrial biodiversity in the area (CEPAL 2009; CR2 2015). The ambiguous standing of knowledge—particularly traditional knowledge—has also been recently debated in the specialized literature. On the one side, traditional practices may offer a form of resilient and sustainable use of local resources which may be lost by recurring only to technology and infrastructure (Montalba et al. 2013, 2015). On the other side, technology and knowledge do offer important adaptation options which are often overlooked especially by the most small-scale, traditional and present-oriented farmer groups (Roco et al. 2014, 2015, 2016). Similarly, the literature seems to agree that the short-term attitude of both farmers and State organizations together with the low empowerment and access to information of local actors appears to be one of the most critical aspects in limiting resilience of the system toward deeper and more longer-term processes such as mega-drought and other climate change-related phenomena (Young et al. 2009; Clarvis and Allan 2014; Hurlbert and Gupta 2016).

Our research on the Limarí Basin, however, allowed us to identify some other aspects which may be actively influencing the way water governance systems affect social–ecological resilience. User organizations particularly emerged as one of the key elements within the Paloma System operating in the Limarí Basin, as well as a potentially rich resilience source for the system spanning all its dimensions from flexibility (as a form of self-regulation), horizontal and vertical connectivity (linking users among themselves and with State institutions), memory and kearning (collecting and directing user practices and fostering knowledge interchange with experts and research institutions), and self-organization (as a driver for local innovation). In our research area, such potential was deeply hampered by a generalized lack of trust and the low legitimacy in the leadership and participation in such organizations. In fact, the growing literature on socioecological systems and adaptive environmental governance has been long stressing the importance of shared trust and polycentric governance as key factors for promoting both the adaptability and the transformability of such systems, especially in the face of growing uncertainties and potential regime shifts caused by climate change (Cosens et al. 2018; Ostrom 2009; Vaas et al. 2017).

Therefore, future research should pay more attention to the role that these organizations (and variables such as trust and legitimacy) play in water management and social–ecological resilience of other basins, both in Chile and in other countries which have been endeavoring in the use of market-based water governance such as Australia, China, South Africa, and/or the USA (Grafton et al. 2010). In more general terms, our results point out the importance of adopting a wider understanding of water scarcity. It is increasingly being accepted that (Mehta 2014) water scarcity is not the mere physical lack of water result (water deficits). It also depends on the structural arrangements determining how the existing water is organized, distributed and employed. In the case of the Limarí Basin, water deficits are an almost endemic phenomenon, a deeply rooted feature of the climatology and geomorphology of the land. In such a context, water scarcity becomes largely self-produced, a result of increasing over-exploitation—itself fostered by the availability of water markets and the outstanding technological infrastructure the basin can count on while growingly threatening the carrying capacity of such infrastructure—together with the absence of territorial planning and an integrated water resources management, short-term attitudes and generalized mistrust leading the system to the critical situation it is now facing. Gravity should not be underestimated particularly in the face of heightened frequency and intensity which droughts are expected to show in the future (Tarhule 2017). Moreover, this outcome would be even more severe if you consider the complex interdependences between water, energy and food dynamics and their respective regulatory framework. This interaction may increase the stress to which water governance institutions are subject to even further, especially in the northern part of Chile (Bauer 2010; Meza et al. 2015).

While the particular social–ecological trajectory the Limarí Basin features may be partly a result of its specific characteristics, our analysis should make us pause on the need of considering water and its management as a combined physical and social process (Linton 2014; Swyngedouw 2009) with deep political and socioenvironmental facets (Boelens et al. 2016) Therefore, they should not be approached through a purely "technical" position focused only on biophysical projections, infrastructure provision and scientific expertise. (Fernandez 2014; Linton and Budds 2014).

Rather a more integrated framework is needed to allow for assessing the reciprocal interactions between social, ecological and technological processes in order to arrange both top-down and bottom-up observations on such processes. A theoretical approach based on the notion of socioecological resilience, as the one we presented in this paper, may offer a very useful model for such framework. This approach may be used not only to study other areas with similar characteristics (additional basins in Chile or other Latin American states), but also to compare the relative performance of different forms of water governance in similar areas as well as suitability of water governance form in different social–ecological systems; finally, it may well serve to push forward a more reflexive and collaborative approach to the planning of water resources and socioecological systems (Sellberg et al. 2018).

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References

Aitken, D., Rivera, D., Godoy-Faúndez, A., & Holzapfel, E. (2016). Water scarcity and the impact of the mining and agricultural sectors in Chile. *Sustainability, 8,* 128. https://doi.org/10.3390/su8020128.

Arnold, R., Troost, C., & Berger, T. (2015). Water resources research. *Water Resources Research, 51,* 648–668. https://doi.org/10.1002/2014WR015382.

Bauer, C. (2010). Dams and markets: Rivers and electric power in Chile. *Natural Resources Journal, 49*(3–4), 583–651.

Bauer, C. (2015). Water conflicts and entrenched governance problems in Chile's market model. *Water Alternatives, 8*(2), 147–172.

Bodin, P., & Wiman, B. (2004). Resilience and other stability concepts in ecology: Notes on their origins, Validity and usefulness. *ESS Bulletin, 2*(2), 33–43.

Boelens, R., Hoogesteger, J., Swyngedouw, E., Vos, J., & Wester, P. (2016). Hydrosocial territories: A political ecology perspective. *Water International, 41*(1), 1–14. https://doi.org/10.1080/02508060.2016.1134898.

Boisier, J., Rondanelli, R., Garreaud, R., & Muñoz, F. (2016). Anthropogenic and natural contributions to the Southeast Pacific precipitation decline and recent megadrought in central Chile. *Geophysical Research Letters, 43*(1), 413–421. https://doi.org/10.1002/2015gl067265.

CEPAL. (2009). *La economía del cambio climático en Chile*. Santiago: CEPAL.

CEPAL/BID. (2010). Cambio Climático una perspectiva regional. In *Cumbre de la Unidad de América Latina y el Caribe*. Riviera Maya (México), 22nd–23rd February, 2010.

Christmann, G., Ibert, O., Kilper, H., Moss, T. (2012). Vulnerability and resilience from a socio-spatial perspective. Towards a theoretical framework. Working Paper 45, Leibniz-Institut für Regionalentwicklung und Strukturplanung eV (IRS).

Clarvis, M. H., & Allan, A. (2014). Adaptive capacity in a Chilean context: A questionable model for Latin America. *Environmental Science & Policy, 43,* 78–90. https://doi.org/10.1016/j.envsci.2013.10.014.

CONAMA. (2008). *Análisis de vulnerabilidad silvoagropecuaria en Chile frente a escenarios de cambio climático*. Santiago: CONAMA.

Cosens, B. A., Gunderson, L., & Chaffin, B. C. (2018). Introduction to the special feature practicing panarchy: Assessing legal flexibility, ecological resilience, and adaptive governance in regional water systems experiencing rapid environmental change. *Ecology and Society, 23*(1), 4. https://doi.org/10.5751/ES-09524-230104.

Costumero, R., Sánchez, J., García-Pedrero, A., Rivera, D., Lillo, M., Gonzalo-Martín, C., et al. (2017). Geography of legal water disputes in Chile. *Journal of Maps, 13*(1), 7–13. https://doi.org/10.1080/17445647.2016.1252803.

CR2. (2015). *La megasequía 2010–2015: Una lección para el futuro*. Santiago: CR2—Centro de Ciencia del Clima y la Resilienca.

Cumming, G. (2011). *Spatial resilience in social–ecological systems*. Cape Town: Springer.

Delgado, L., Torres-Gómez, M., Tironi-Silva, A., & Marín, V. (2015). Estrategia de adaptación local al cambio climático para el acceso equitativo al agua en zonas rurales de Chile. *América Latina hoy, 69,* 113–137.

Denzin, N., & Lincoln, Y. (2011). *Handbook of qualitative research* (4th ed.). Thousand Oaks: Sage Publications.

Díaz, R. (2008). *El recurso hídrico: acceso, reglas y restricciones en zonas áridas, Cuenca del limarí*. La Serena: Universidad de La Serena.

Donoso, G. (2003). *Mercados de Agua: Estudio de Caso del Código de Aguas en Chile de 1981*. Santiago: Pontificia Universidad Católica de Chile.

Doughty, C. A. (2016). Building climate change resilience through local cooperation: A Peruvian Andes case study. *Regional Environmental Change, 16*(8), 2187–2197. https://doi.org/10.1007/s10113-015-0882-2.

Engle, N. (2011). Adaptive capacity and its assessment. *Global Environmental Change, 21*(2), 647–656. https://doi.org/10.1016/j.gloenvcha.2011.01.019.

FAO. (2010). *Gestión del Riesgo de sequía y otros eventos climáticos extremos en Chile*. Santiago: FAO.

Favier, V., Falvey, M., Rabatel, A., Praderio, E., & López, D. (2009). Interpreting discrepancies between discharge and precipitation in high-altitude area of Chile's Norte Chico region (26–32°S). *Water Resources Research, 45*(2), W02424. https://doi.org/10.1029/2008WR006802.

Fernandez, S. (2014). Much Ado about minimum flows… Unpacking indicators to reveal water politics. *Geoforum, 57,* 258–271. https://doi.org/10.1016/j.geoforum.2013.04.017.

Ferrando, F. (2002). Cuenca del Río Limarí, Chile Semiárido: Aspectos de la Oferta y Demanda de Agua. *Rev Geogr Norte Gd, 30,* 23–44.

Folke, C. (2006). Resilience: The emergence of a perspective for social–ecological systems. *Global Environmental Change, 16*(3), 253–267. https://doi.org/10.1016/j.gloenvcha.2006.04.002.
Folke, C. (2016). Resilience. *Oxford research encyclopedia of environmental science*. http://environmentalscience.oxfordre.com/view/10.1093/acrefore/9780199389414.001.0001/acrefore-9780199389414-e-8. Accessed 8 September, 2017.
Folke, C., Hahn, T., Olsson, P., & Norberg, J. (2005). Adaptive governance of social–ecological systems. *Annual Review of Environment and Resources, 30,* 441–473. https://doi.org/10.1146/annurev.energy.30.050504.144511.
Frêne, C., Ojeda, G., Santibáñez, J., Donoso, C., Sanzana, J., Molina, C., et al. (2014). Agua en Chile: diagnósticos territoriales y propuestas para enfrentar la crisis hídrica. Aguas que has de beber, Santiago. http://bosquenativo.cl/wp-content/uploads/2016/01/agua_en_chile_propuestas_2014.pdf. Retrieved 4 June, 2018.
Fuster, R. (2006). *Equidad en el acceso al agua en la agricultura. Evaluación del modelo chileno de gestión de las aguas: El caso de la cuenca del río Limarí*. Barcelona: Universitat Autònoma de Barcelona/ICTA.
Galaz, V. (2004). Stealing from the poor? Game theory and the politics of water markets in Chile. *Environmental Politics, 13*(2), 414–437.
Gallopin, G. (2006). Linkages between vulnerability, resilience, and adaptive capacity. *Global Environmental Change, 16*(3), 293–303. https://doi.org/10.1016/j.gloenvcha.2006.02.004.
Gentes, I. (2007). *Las aguas transadas. Estado de arte de las propiedades hidráulicas y del impacto del mercado de derechos de agua en Chile*. Santiago de Chile: OXFAM.
Gotts, N. (2007). Resilience, panarchy, and world-systems analysis. *Ecology and Society, 12*(1), 24–37.
Grafton, R. Q., Landry, C., Libecap, G. D., McGlennon, S., O'Brien, R. (2010). An integrated assessment of water markets: Australia, Chile, China, South Africa and the USA. National Bureau of Economic Research, Cambridge MA, Working Paper 16203. http://www.kysq.org/docs/Grafton%20et%20al%202010.pdf. Accessed 4 June, 2018.
Gunderson, L., & Holling, C. (2002). *Panarchy: Understanding transformations in human and natural systems*. Washington: Island Press.
Hadjigeorgalis, E. (2004). Comerciando con incertidumbre: Los mercados de agua en la agricultura chilena. *Cuad Econ, 41*(122), 3–34. https://doi.org/10.4067/S0717-68212004012200001.
Haughton, G. (2002). Market making: Internationalisation and global water markets. *Environment and Planning A, 34,* 791–807. https://doi.org/10.1068/a3426.
Hearne, R., & Donoso, G. (2014). Water markets in Chile: Are they meeting needs? In W. Easter & Q. Huang (Eds.), *Water markets for the 21st century* (pp. 103–126). Berlin: Springer.
Holling, C. (1973). Resilience and stability of ecological systems. *Annual Reviews of Ecology and Systematics, 4,* 1–23.
Hurlbert, M., & Gupta, J. (2016). The adaptive capacity of institutions in Canada, Argentina, and Chile to droughts and floods. *Regional Environmental Change, 17*(3), 865–877. https://doi.org/10.1007/s10113-016-1078-0.
Ifejika, C. (2013). Buffer capacity: Capturing a dimension of resilience to climate change in African smallholder agriculture. *Regional Environmental Change, 13*(3), 521–535. https://doi.org/10.1007/s10113-012-0391-5.
INDH - Instituto Nacional de Derechos Humanos. (2016). Mapa de conflictos socioambientales en Chile 2015. http://bibliotecadigital.indh.cl/handle/123456789/989. Retrieved 4 June, 2018.
Jara-Rojas, R., Bravo-Ureta, B. E., & Díaz, J. (2012). Adoption of water conservation practices: A socioeconomic analysis of small-scale farmers in Central Chile. *Agricultural Systems, 110,* 54–62. https://doi.org/10.1016/j.agsy.2012.03.008.
Karoly, D. (1989). Southern hemisphere circulation features associated with El Niño-Southern Oscillation events. *Journal of Climate, 2*(11), 1239–1252.
Leon, A. (2008). Políticas macroeconómica y de promoción del riego y cambio climático en la montaña semi-árida de chile. *Pirineos, 163,* 111–133. https://doi.org/10.3989/pirineos.2008.v163.26.
Linton, J. (2014). Modern water and its discontents: A history of hydrosocial renewal. *WIREs Water, 1,* 111–120. https://doi.org/10.1002/wat2.1009.
Linton, J., & Budds, J. (2014). The hydrosocial cycle: Defining and mobilizing a relational-dialectical approach to water. *Geoforum, 57,* 170–180. https://doi.org/10.1016/j.geoforum.2013.10.008.
Mantua, N., & Hare, S. (2002). The Pacific decadal oscillation. *Journal of Oceanography, 58*(1), 35–44.
Mehta, L. (2014). Water and human development. *World Development, 59,* 59–69. https://doi.org/10.1016/j.worlddev.2013.12.018.

Meza, F. (2013). Recent trends and ENSO influence on droughts in Northern Chile: An application of the Standardized Precipitation Evapotranspiration Index. *Weather and Climate Extremes, 1,* 51–58. https://doi.org/10.1016/j.wace.2013.07.002.

Meza, F., Vicuna, S., Gironás, J., Poblete, D., Suárez, F., & Oertel, M. (2015). Water–food–energy nexus in Chile: The challenges due to global change in different regional contexts. *Water International, 40*(5–6), 839–855. https://doi.org/10.1080/02508060.2015.1087797.

Meza, F., Wilks, D., Gurovich, L., & Bambach, N. (2012). Impacts of climate change on irrigated agriculture in the Maipo Basin, Chile: Reliability of water rights and changes in the demand for irrigation. *Journal of Water Resources Planning and Management, 138,* 421–430. https://doi.org/10.1061/(ASCE)WR.1943-5452.

Ministerio del Medio Ambiente. (2016). *Tercera Comunicación Nacional de Chile ante la Convención Marco de las Naciones Unidas sobre Cambio Climático*. Santiago: Ministerio del Medio Ambiente.

Molinos-Senante, M., Donoso, G., & Sala-Garrido, R. (2016). Are participants in markets for water rights more efficient in the use of water than non-participants? A case study for Limarí valley (Chile). *Environmental Science and Pollution Research, 23,* 10665–10678. https://doi.org/10.1007/s11356-016-6187-2.

Montalba, R., Fonseca, F., García, M., Vieli, L., & Altieri, M. (2015). Determinación de los niveles de riesgo socioecológico ante sequías en sistemas agrícolas campesinos de La Araucanía chilena. Influencia de la diversidad cultural y la agrobiodiversidad. *Papers, 100*(4), 607–624. https://doi.org/10.5565/rev/papers.2168.

Montalba, R., García, M., Altieri, M., Fonseca, F., & Vieli, L. (2013). Utilización del Índice Holístico de Riesgo (IHR) como medida de resiliencia socioecológica a condiciones de escasez de recursos hídricos. Aplicación en comunidades campesinas e indígenas de la Araucanía, Chile. *Agroecología, 8*(1), 63–70.

Montaña, E., Diaz, H., & Hurlbert, M. (2016). Development, local livelihoods, and vulnerabilities to global environmental change in the South American Dry Andes. *Regional Environmental Change, 16*(8), 2215–2228. https://doi.org/10.1007/s10113-015-0888-9.

Nauditt, A., Kretschmer, N., Ribbe, L. (2010). Limarí River Basin study phase I—Current conditions, history and plans. Institute for Technology and Resources Management in the Tropics and Subtropics. http://www.harcresearch.org/sites/default/files/Project_Documents/Limari%20River%20Basin%20Study%20Phase%20I%20-%20Central%20Chile%20-%20Current%20conditions,%20history%20and%20plans.pdf. Accessed 8 September, 2017.

Núñez, J., Rivera, D., Oyarzún, R., Arumí, J. (2013a). Chile a secas: vulnerabilidad chilena frente a la sequía y déficit hídrico extremo desde la interfaz ciencia-política. Documentos de Trabajo Instituto de Políticas Públicas UDP 15, Santiago.

Núñez, J., Rivera, D., Oyarzún, R., & Arumí, J. (2013b). Influence of pacific ocean multidecadal variability on the distributional properties of hydrological variables in north-central Chile. *Journal of Hydrology, 501,* 227–240. https://doi.org/10.1016/j.jhydrol.2013.07.035.

Nykvist, B. (2012). *Social learning in the Anthropocene. Governance of natural resources in human dominated systems*. Stockholm: Stockholm University.

Olsson, P., Folke, C., & Hahn, T. (2004). Social–ecological transformation for ecosystem management: The development of adaptive co-management of a wetland landscape in Southern Sweden. *Ecology and Society, 9*(4), 2.

Olsson, P., Gunderson, L., Carpenter, S., Ryan, P., Lebel, L., Folke, C., et al. (2006). Shooting the rapids: Navigating transitions to adaptive governance of social–ecological systems. *Ecology and Society, 11*(1), 18.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*. Cambridge: Cambridge University Press.

Ostrom, E. (2009). A polycentric approach for coping with climate change. World Bank eLibrary. Policy research working papers, The World Bank. https://doi.org/10.1596/1813-9450-5095.

Oyarzún, J., & Oyarzún, R. (2011). Sustainable development threats, inter-sector conflicts and environmental policy requirements in the arid, mining rich, northern Chile territory. *Sustainable Development, 19,* 263–274. https://doi.org/10.1002/sd.441.

Peña, H., Luraschi, M., & Valenzuela, S. (2004). Agua, desarrollo y políticas públicas: la experiencia de Chile. *REGA, 1*(2), 25–50.

Prieto, M. (2016). Bringing water markets down to Chile's Atacama Desert. *Water International, 41*(2), 191–212. https://doi.org/10.1080/02508060.2015.1107400.

Qin, H., Romero-Lankao, P., Hardoy, J., & Rosas-Huerta, A. (2015). Household responses to climate-related hazards in four Latin American cities: A conceptual framework and exploratory analysis. *Urban Climate, 14,* 94–110. https://doi.org/10.1016/j.uclim.2015.05.003.

Retamal, R., Andreoli, A., Arumi, J., & Rojas, J. (2013). Gobernanza Del Agua Y Cambio Climático: Fortalezas Y Debilidades Del Actual Sistema De Gestión Del Agua En Chile. Análisis interno. *Interciencia, 38*(1), 8–16.

Retamal, R., Melo, O., Arumí, J., & Parra, O. (2012). Sustainable water governance in Chile: From a sectoral management system to an integrated one? In D. Rivera (Ed.), *Chile: Environmental, political and social issues* (pp. 33–68). Santiago: Nova Publishers.

Retamal, R., Rojas, J., & Parra, O. (2011). Percepción al cambio climático y a la gestión del agua: aportes a las estrategias metodológicas cualitativas para su comprensión. *Ambiente & Sociedade, 14*(1), 175–194.

Rey, D., Holman, I., & Knox, J. (2017). Developing drought resilience in irrigated agriculture in the face of increasing water scarcity. *Regional Environmental Change, 17*(5), 1527–1540. https://doi.org/10.1007/s10113-017-1116-6.

Rivera, D., Godoy-Faúndez, A., Lillo, M., Alvez, A., Delgado, V., Gonzalo-Martín, C., et al. (2016). Legal disputes as a proxy for regional conflicts over water rights in chile. *Journal of Hydrology, 535,* 36–45. https://doi.org/10.1016/j.jhydrol.2016.01.057.

Roco, L., Engler, A., Bravo-Ureta, B., & Jara-Rojas, R. (2014). Farm level adaptation decisions to face climatic change and variability: Evidence from Central Chile. *Environmental Science & Policy, 44,* 86–96. https://doi.org/10.1016/j.envsci.2014.07.008.

Roco, L., Engler, A., Bravo-Ureta, B. E., & Jara-Rojas, R. (2015). Farmers' perception of climate change in mediterranean Chile. *Regional Environmental Change, 15*(5), 867–879. https://doi.org/10.1007/s10113-014-0669-x.

Roco, L., Poblete, D., Meza, F., & Kerrigan, G. (2016). Farmers' options to address water scarcity in a changing climate: Case studies from two Basins in Mediterranean Chile. *Environmental Management, 58*(6), 958–971. https://doi.org/10.1007/s00267-016-0759-2.

Rojas, J. (2013). *Impactos sociales y ambientales del cambio climático global en la región del Bío Bío. Desafíos para la sostenibilidad del siglo XXI*. Concepción: Universidad de Concepción.

Rojas, J. (2016). Desafíos epistemológicos de la comprensión interdisciplinaria de los sistemas socioecológicos que sustentan la vida en la era global y de cambio climático. In R. Barra & J. Rojas (Eds.), *Desarrollo sustentable. Miradas interdisciplinarias de experiencias en Chile y Brasil*. Concepción: Universidad de Concepción.

Saterfiel, T., Gregory, R., Klain, S., Roberts, M., & Chan, K. (2013). Culture, intangibles and metrics in environmental management. *Journal of Environmental Management, 117*(15), 103–114. https://doi.org/10.1016/j.jenvman.2012.11.033.

Sellberg, M. M., Ryan, P., Borgström, S. T., Norström, A. V., & Peterson, G. D. (2018). From resilience thinking to resilience planning: Lessons from practice. *Journal of Environmental Management, 217*(1), 906–918. https://doi.org/10.1016/j.jenvman.2018.04.012.

Sietz, D., & Feola, G. (2016). Resilience in the rural Andes: Critical dynamics, constraints and emerging opportunities. *Regional Environmental Change, 16*(8), 2163–2169. https://doi.org/10.1007/s10113-016-1053-9.

Strauch, G., Oyarzún, R., Reinstorf, F., Oyarzún, J., Schirmer, M., & Knöller, K. (2009). Interaction of water components in the semi-arid Huasco and Limarí river basins, North Central Chile. *Advanced Geosciences, 22,* 51–57.

Swyngedouw, E. (2009). The political economy and political ecology of the hydro-social cycle. *Journal of Contemporary Water Research and Education, 142,* 56–60. https://doi.org/10.1111/j.1936-704X.2009.00054.x.

Tarhule, A. (2017). The future of water: Prospects and challenges for water management in the 21st century. In J. R. Ziolkowska & J. M. Peterson (Eds.), *Competition for water resources. Experiences and management approaches in the US and Europe* (pp. 442–454). Amsterdam: Elsevier. https://doi.org/10.1016/b978-0-12-803237-4.00025-2.

Tompkins, E., & Adger, N. (2004). Does adaptive management of natural resources enhance resilience to climate change? *Ecology and Society, 9*(2), 10.

Urquiza, A., & Cadenas, H. (2015). Sistemas socio-ecológicos: elementos teóricos y conceptuales para la discusión en torno a vulnerabilidad hídrica. *L'Ordinaire des Amériques, 218,* 1–22. https://doi.org/10.4000/orda.1774.

Vaas, J., Driessen, P. J., Giezen, M., van Laerhoven, F., & Wassen, M. J. (2017). Who's in charge here anyway? Polycentric governance configurations and the development of policy on invasive alien species in the semisovereign. *Ecology and Society, 22*(4), 1. https://doi.org/10.5751/ES-09487-220401.

Valdés-pineda, R., Pizarro, R., García-chevesich, P., Valdés, J., Olivares, C., Vera, M., et al. (2014). Water governance in Chile: Availability, management and climate change. *Journal of Hydrology, 519,* 2538–2567. https://doi.org/10.1016/j.jhydrol.2014.04.016.

Vargas, X. (2012). *Disponibilidad futura de los recursos hídricos frente a escenarios de cambio climático en Chile*. Santiago de Chile: CEPAL.
Vergara, A. (2015). Crisis institucional del agua. Descripción del modelo, crítica a la burocracia y propuesta de tribunales especiales. Thomson Reuters. http://vergarablanco.cl/2015-crisis-institucional-del-agua-descripcion-del-modelo-critica-la-burocracia-propuesta-tribunales-especiales/. Accessed 8 September, 2017.
Vicuña, S., Alvarez, P., Melo, O., Dale, L., & Meza, F. (2014). Irrigation infrastructure development in the Limarí Basin in Central Chile: Implications for adaptation to climate variability and climate change. *Water International, 39*(5), 620–634. https://doi.org/10.1080/02508060.2014.945068.
Vicuña, S., McPhee, J., & Garreaud, R. (2012). Agriculture vulnerability to climate change in a snowmelt driven basin in semiarid Chile. *Journal of Water Resources Planning and Management, 138*(5), 431–441. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000202.
Walker, B., Holling, C., Carpenter, S., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society, 9,* 5.
Walker, B., & Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Washington: Island Press.
World Bank. (2011). Diagnóstico de la gestión de los recursos hídricos. http://www.dga.cl/eventos/Diagnostico%20gestion%20de%20recursos%20hidricos%20en%20Chile_Banco%20Mundial.pdf. Accessed 8 September, 2017.
World Bank. (2013). Estudio para el mejoramiento del marco institucional para la gestión del agua. http://reformacodigodeaguas.carey.cl/wp-content/uploads/2014/09/Informe-Banco-Mundial-Estudio-para-el-mejoramiento-del-marco-institucional.pdf. Accessed 8 September, 2017.
Young, G., Zavala, H., Wandel, J., Smit, B., Salas, S., Jimenez, E., et al. (2009). Vulnerability and adaptation in a dryland community of the Elqui Valley, Chile. *Climate Change, 98*(1–2), 245–276. https://doi.org/10.1007/s10584-009-9665-4.

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