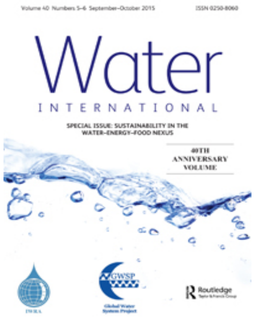

Water International

ISSN: 0250-8060 (Print) 1941-1707 (Online) Journal homepage: https://www.tandfonline.com/loi/rwin20

Water–food–energy nexus in Chile: the challenges due to global change in different regional contexts

Francisco J. Meza, Sebastian Vicuna, Jorge Gironás, David Poblete, Francisco Suárez & Melanie Oertel

To cite this article: Francisco J. Meza, Sebastian Vicuna, Jorge Gironás, David Poblete, Francisco Suárez & Melanie Oertel (2015) Water–food–energy nexus in Chile: the challenges due to global change in different regional contexts, Water International, 40:5-6, 839-855, DOI: 10.1080/02508060.2015.1087797

To link to this article: https://doi.org/10.1080/02508060.2015.1087797

Published online: 14 Sep 2015.

Water International, 2015
Vol. 40, Nos. 5–6, 839–855, http://dx.doi.org/10.1080/02508060.2015.1087797

Water–food–energy nexus in Chile: the challenges due to global change in different regional contexts

Francisco J. Meza[a,b,c]*, Sebastian Vicuna[a,c], Jorge Gironás[a,d,e], David Poblete[a], Francisco Suárez[d,e] and Melanie Oertel[a]

[a]*Centro Interdisciplinario de Cambio Global, Pontificia Universidad Católica de Chile, Santiago, Chile;* [b]*Departamento de Ecosistemas y Medio Ambiente, Pontificia Universidad Católica de Chile, Santiago, Chile;* [c]*Aquasec, IAI Center of Excellence for Water Security, Santiago, Chile;* [d]*Departamento de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile, Santiago, Chile;* [e]*Centro de Desarrollo Urbano Sustentable CONICYT/FONDAP/15110020, Santiago, Chile*

(*Received 1 October 2014; accepted 24 August 2015*)

This paper modifies the traditional representation of the water–food–energy (WFE) nexus by emphasizing the flows or influences between components. This allows a better representation of the dynamic nature of the WFE nexus in response to global change drivers. It applies a conceptual figure to synthesize the status and future challenges of the nexus in four regions of Chile that are currently under pressure due to climate variability, relative water scarcity and strong competition for water from different sectors.

Keywords: basin scale; global change challenges; nexus communication; Chile

Introduction

A significant contribution of the water–food–energy (WFE) nexus idea is the ability to communicate complex systems interactions and dependences among its elements. However, the way in which is traditionally depicted does not allow one to identify changes in its components and relationships as a consequence of global change drivers, limiting its applicability to communicate future challenges to stakeholders and policy-makers. It is a task of scientists to communicate the WFE nexus clearly and to offer options how to deal with it (Finley & Seiber, 2014).

The aim of this paper is to illustrate the nature of the WFE nexus in four regions of Chile that are currently under pressure due to climate variability, relative water scarcity and that suffer from strong competition among their users. Furthermore, global change is expected to have significant impacts on these regions. A synthesis of this analysis is presented by means of a conceptual figure that allows the better communication of the status of the WFE nexus, and highlights its dynamic nature in response to external driving forces.

Illustrating the WFE nexus status and changes

A commonly used image to present the WFE nexus concept is a Venn diagram where the intersections of individual sets (energy security, water security and food security) depict the nexus. The simplicity of this approach is definitively a merit, but it does not allow the

*Corresponding author. Email: fmeza@uc.cl

incorporation of dynamic driving forces, such as the ones associated with global environmental change. Furthermore, it cannot be used to determine tradeoffs and/or synergies among the components of the nexus.

We have adopted a different approach in which systems are treated as separate units connected by arrows. These arrows indicate influence or supply (if a quantitative approach is to be followed) or demands in case of a reciprocal relationship. Within this framework, the dynamic nature of the WFE nexus is represented as changes in the size of the units, their composition and/or by changes in the influence exerted by other systems. Since the driving forces of the global change are connected directly or indirectly to each of the components of the WFE nexus, the main hypothesis of our work is that global change (especially climate change) will affect the nature of the WFE nexus, turning it eventually into a more complex and vulnerable system.

The presented graphical approach, as a communication tool, helps to raise awareness in a simple and effective manner. It is not an analytical tool in itself, but as the WFE nexus is still something 'new' in stakeholder discussions it is important to offer something handy for descriptively purposes. Therefore, our proposed illustrative tool serves to visualize existing and possible future tradeoffs. It can be useful especially in scenario analysis as it allows, in the ideal and envisaged case, the identification of win–win solutions as well. Hereby, adaptation measures can be discussed accordingly.

Figure 1 presents our conceptual definition of the WFE nexus with emphasis on the most common interactions that apply in the context of Chile. Arrows represent supply flows provided – or demands exerted – by each subsystem and thus imbalances between both generate problems of water, food and/or energy security. One strength of the graphic is its flexible entry point (energy or water or food), therefore the analysis of a region with respect to the WFE nexus can be done from any starting point. Each system has been divided to allow a

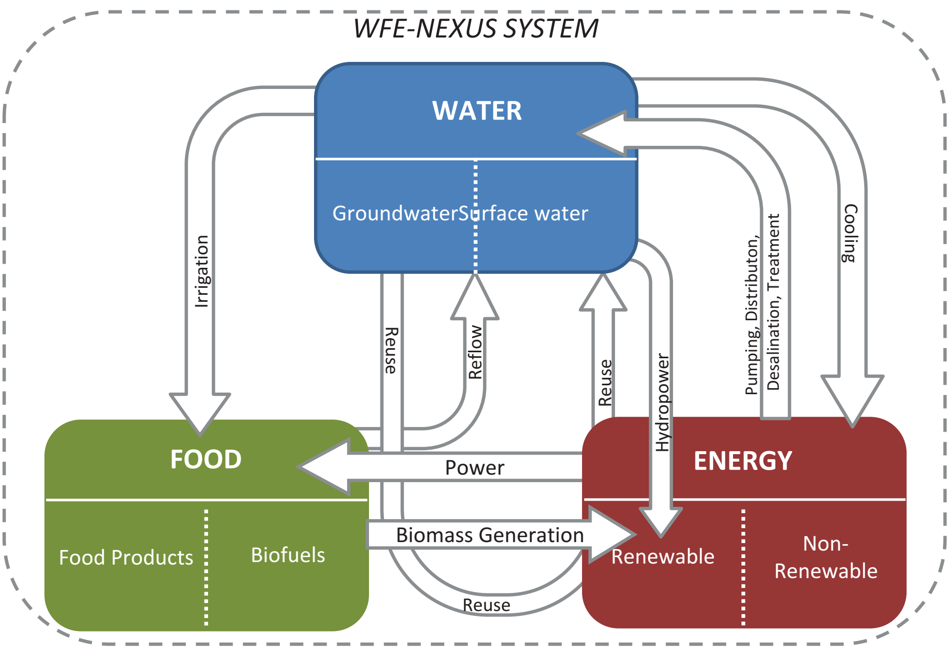

Figure 1. The WFE nexus; arrows illustrate supply relationships between systems.

more specific representation of the current situation and/or the potential effect that global change will have on the WFE nexus. Energy is divided into renewable (i.e. hydropower, wind, solar, biofuels, etc.) and non-renewable sources (those directly associated with greenhouse gas emissions from fossil fuels). The food system can deliver traditional goods and services as well as biofuels. Although the label *Food* does not properly represent the complexity of the system, we have maintained it for simplicity as it is widely used. An alternative would have been to replace it by *Land* as presented by Ringler, Bhaduri, and Lawford (2013). Finally the water system is divided into surface water (because its relevance for hydropower generation) and groundwater (which demands energy for pumping).

WFE nexus modification as a consequence of global change could occur either by increasing the number of arrows representing interactions and/or changing the start or end point of them. The size of the arrows can be used to communicate magnitudes of the supply (demand), whereas competition is represented by several arrows coming from the same source. The relative size of each subdivision and its change over time can be seen as an indicator of sensitivity of each system. A WFE nexus that does not change substantially under global change could be interpreted as non-vulnerable or even resilient, if adjustments over time occur without major external intervention.

Nexus status and challenges: case studies from Chile

Here we illustrate the use the WFE nexus conceptual framework in four different case study regions for Chile's WFE nexus (Figure 2). These cases are placed in regions that are prone to suffer from water security problems (such as droughts, increasing competition

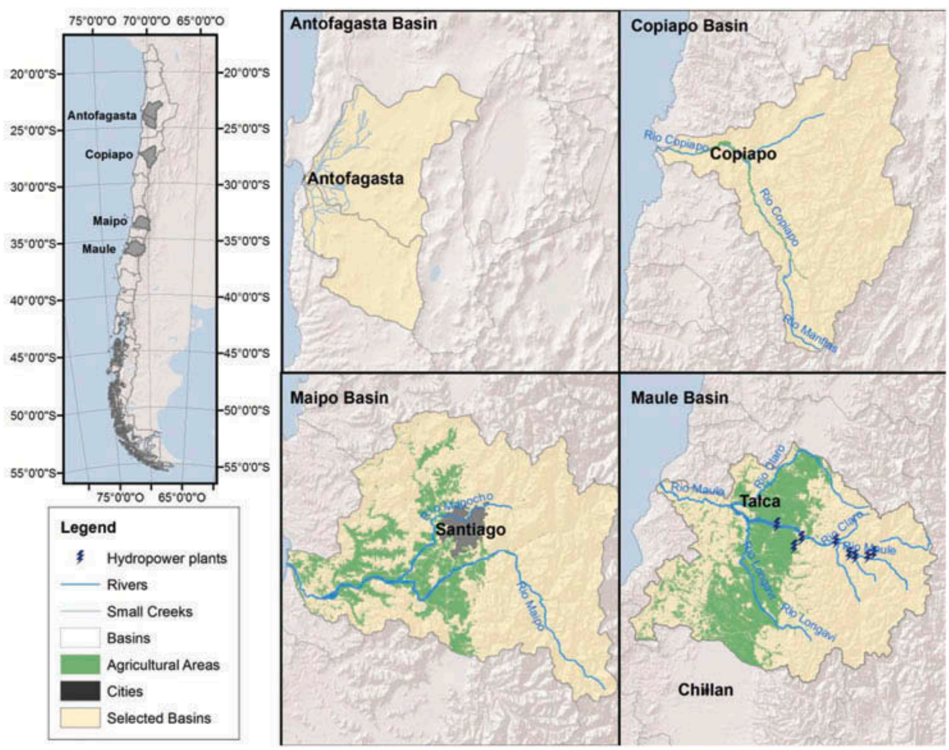

Figure 2. Location of the four Chilean case studies for WFE nexus analysis.

and over-allocation of water resources). Moreover, they collectively represent a sample of WFE nexus problems that are commonly found in arid and Mediterranean areas of fast growing economies.

Chile presents a wide variety of climatic regimes, which are the result of the combination of its latitudinal extension, the presence of the Pacific Ocean and an irregular topography dominated by the Andes Cordillera. Along its territory it is possible to observe the transition from the driest dessert in the world to a Mediterranean climate, and then move towards temperate oceanic and sub-polar oceanic environments in the central and southern parts of the country.

In the arid and semi-arid zones located in northern Chile rivers originate in the highest catchments of the cordillera and exhibit perennial and semi-perennial flows. In the central part of the country snow-dominated basins are the most frequent ones, showing a nival regime, with the highest flows occurring in mid-spring to early summer (September–January). As we move south, streamflows increase substantially, rivers with mixed and pluvial regimes start to appear, and flow seasonality changes as a consequence of a more marked influence of the rainfall concentrated between April and September.

Mean annual temperatures in Chile show little fluctuation along the coast due to the influence of the Humboldt current. While the northern part exhibit mean temperatures of 17°C, the austral part shows mean values of 6°C. Recent temperature variations in several meteorological stations of Chile show warming rates between 1.3 and 2.0°C per century for 1933–92 (Rosenbluth, Funzalida, & Aceituno, 1997). More recent data indicate that temperature trends show spatial heterogeneity (Falvey & Garreaud, 2009), with a strong contrast between surface cooling at coastal stations (−0.2°C/decade) and warming in the Andes (0.25°C/decade).

A slight decrease in annual precipitation has been observed in Peru and southern Chile (Haylock et al., 2006). Data from Santiago (one of the oldest meteorological stations in operation) exhibit a modest secular decline in total annual precipitation (Luckman & Villalba, 2001). Severe dry conditions have been observed recently in most of central and northern Chile. Traditional drought indices have been used to document this feature. In the Coquimbo region the occurrence of dry conditions of different magnitude has increased over the last decades, and the duration of extreme climatic events has slightly increased as well (Meza, 2013).

Regional results developed using results from global circulation models (GCM) as boundary conditions (HadCM3 under SRES scenarios A2 and B2) show potential changes in temperature in the order of 2–4°C by the end of the century, with the highest increases in temperature in the Andean regions (Fuenzalida et al., 2007). Higher temperatures and a reduction in rainfall will affect snowmelt-driven rivers advancing peak hygrograms and reducing annual discharges (Hayhoe et al., 2004; Vicuna, Dracup, Lund, Dale, & Maurer, 2010). Accordingly, it is likely that demands could not be met as existing water rights will not yield the expected flow to users (Meza, Wilks, Gurovich, & Bambach, 2012).

WFE nexus in the Antofagasta region

The Antofagasta region covers a large proportion (126,000 km^2) of what is called the ‘Norte Grande’ (Large North) region in northern Chile (21–26° S). Unique to the region is that it encompasses a large portion of the Atacama Desert, the driest on Earth. Copper mining is the main economic driver in the Antofagasta region contributing to over 65% of the regional gross domestic product (GDP), thus increasing the per capita income in the region well above the country average.

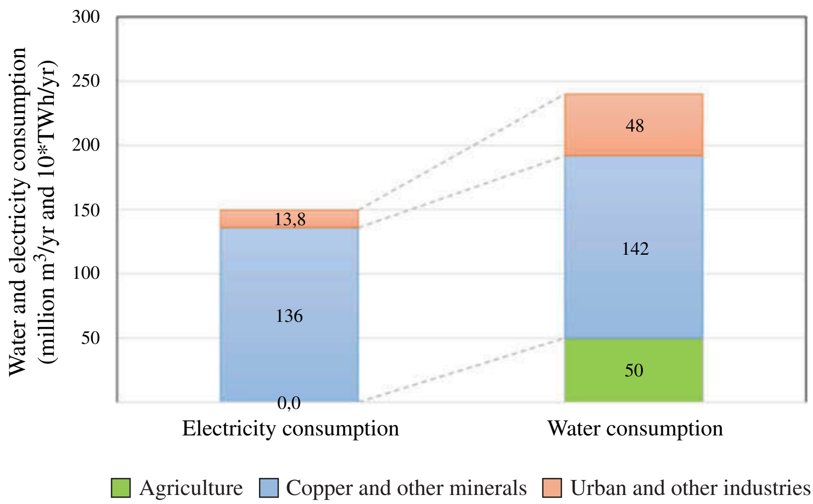

Figure 3. Annual water and electricity consumption patterns in the Antofagasta region.

Only 2.3% of the population lives in rural areas. Agriculture here is carried out by smallholder farmers who are mostly pastoralists, and with a small participation of irrigated agriculture based on horticultural crops.

The copper-mining industry is the main consumer of water and energy resources in the region, as can be appreciated in Figure 3. If we consider the country as a whole, mining consumes less than 6% of total water compared with 72% and 23% for agriculture and the urban sector respectively. In the Antofagasta region, the proportion of water consumed by the mining sector accounts for almost 60%, whereas the other 40% is shared between the urban and agriculture sectors. In terms of electricity consumption, the role of mining is rising to more than 90%, leaving the rest to urban and some other non-mining industries.

Driven by extreme dry conditions and because of the small size of agriculture, the WFE nexus has started functioning already in the form of an energy toll via desalination and uphill pumping to deliver freshwater to one of the copper mines and the city of Antofagasta. With the expected increases in both population and copper production, the WFE nexus will be exacerbated in future. Since there are few surface or groundwater resources available in the region, and they would probably experience a reduction as a consequence of climate change impacts on precipitation, the only option that both industries have to accommodate the associated increase in water resources consumption is via saltwater desalination. Figure 4 shows the current and future status of the WFE nexus in this region. Here mining is considered as an external consumer in the WFE nexus system.

It is expected that copper production will increase by 20% in the next 10 years. The water needed to support this increase in production would be around 30 Mm^3/year. Considering an energy cost of 4 kWh/m^3 of desalted water and 13 kWh/m^3 of water pumped 3000 m to the mines' locations, this amount of water will increase electricity consumption by 0.5 TWh/year. The overall future needs of electricity generation in the region due to expanded copper production and increase in population is around 600 MW. A total of 70% of this increase, considering renewable energy regulations and technological and price restrictions, will be met via thermoelectric (coal) generation; the rest

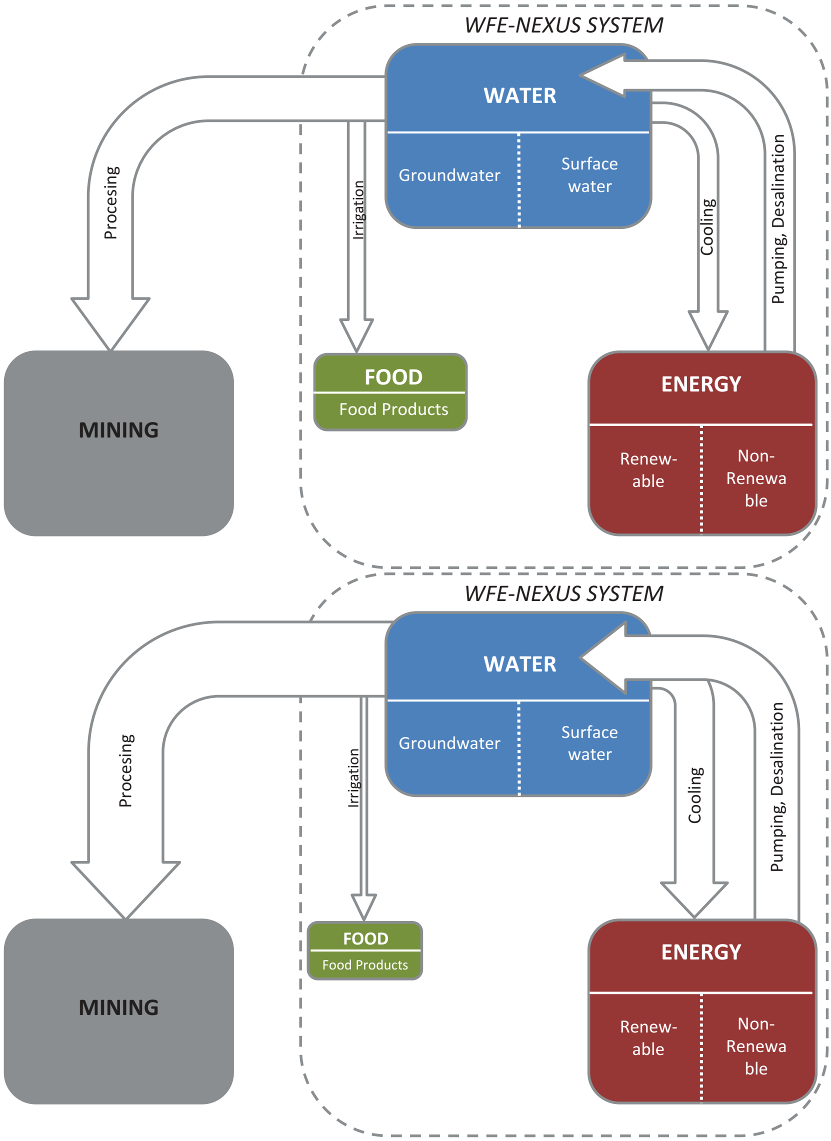

Figure 4. WFE nexus in the Antofagasta region. Current and future conditions are depicted in the upper and lower panels respectively.

should be met by a combination of solar, wind and geothermal renewable generation. In most of cases (except wind and solar) there is a further increase in water consumption for cooling that further exacerbates the WFE nexus.

Currently there is little or no connection between food and energy as smallholder pastoralists do not require power (i.e. tractor) and normally do not use fertilizers that require oil for their production. The size of agriculture is small and concentrated only on food products with no potential to produce biomass (biofuels). Future projections of climate indicate that the availability of water resources will decrease (although no consensus exist among GCMs). Because of its small relative size, increasing competition from mining and reduced availability, the food system will become even smaller and probably the total amount of water from irrigation will decrease accordingly.

The WFE nexus in Antofagasta is rather simple. Water is a key component and serves a small agriculture sector as well as large mining operations. Energy is used to distribute water and meet the demands from mining. Future global changes would alter the WFE nexus by increasing the demand for energy for pumping and more water will be allocated to the mining sector. As a consequence, small horticulture will be reduced. Although the region is currently not self-sufficient in terms of food production, future scenarios will likely affect the WFE nexus, reducing the food component to an even smaller component.

WFE nexus in the Copiapó region

Located in the Atacama region, the Copiapó River basin (with an area of 18,538 km^2) represents a true example of an arid basin under tremendous and increasing water stress due to constantly growing demands from crop irrigation, urban water supply, the mining industry and tourism (Suárez et al., 2014). The average annual precipitation over the basin is 28 mm, the average daily solar radiation is 220 Wm^{-2}, and the average pond evaporation is about 2650 mm/year (DICTUC, 2010). The mean annual temperature is 17.8°C, whereas the spatial average of the monthly mean temperatures ranges between 14.4 and 21°C (DICTUC, 2010). Cycles of dry and humid years are common, most likely due to the El Niño Southern Oscillation phenomenon (Oyarzún & Oyarzún, 2011). The Copiapó River has a mixed hydrological regime, dominated mostly by snowmelt above 1200 m, and a combination of snowmelt and rainfall below this elevation (DGA, 2013). Its flow regime varies temporarily and spatially due to water extractions for irrigation and surface-to-subsurface interactions. Monthly average flows at the 'Río Copiapó en La Puerta' and 'Río Copiapó en Angostura' flow gauges range between 2.08 and 2.93 m^3/s and between 0.26 and 0.67 m^3/s respectively. These two gauges record water inputs and outputs to the main close groundwater system.

Figure 5 shows the temporal evolution of the aquifer storage volume since 1974 based on water level records in wells within the basin. Groundwater storage is depleting starting from 1995 due to the combined effect of drought and increasing water use by the different users (Suárez et al., 2014). Moreover, an average reduction of 50 Mm^3/s has been observed since 2007, which implies that an extra flow supply of about 1.6 m^3/s is needed to satisfy current average consumption. Finally, this groundwater depletion implies worse water quality and more energy required for pumping.

The main water users in the basin are the agriculture, mining and residential sectors. Agriculture (mostly table grapes and olives and other vegetables) and mining (copper, iron, gold and silver) are the main economic activities and have brought the basin to a highly strategic position within northern Chile. These sectors employ 7.6% and 19.6% of the labour force of the Atacama region respectively. The needs of consumptive water from these sectors are significant, as shown in Table 1, which presents the water rights given to them as well as to the residential sector (potable water) and other industries (DICTUC, 2010). Table 1 also shows the estimated current water demands obtained from the calibrated integrated water management model developed by DICTUC (2010) and presented by Suárez et al. (2014). Around 56% of water rights were given for crop irrigation (about 90% drip irrigation), although about 80% of the water currently used in the basin (6 m^3/s) is estimated to be demanded by this activity. Using records from the extraction wells, DGA (2013) estimated water demands of about 0.620 m^3/s and about 0.680 m^3/s for the mining sector and residential water sector respectively during 2012. Most of the fresh water used by agriculture is groundwater, as well as the totality of the water for residential use. Thus, a significant amount of

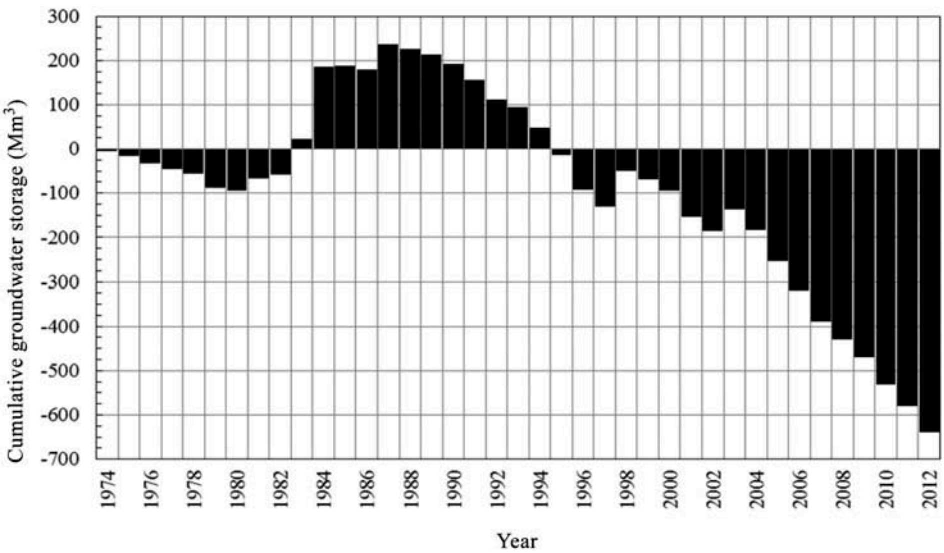

Figure 5. Cumulative aquifer storage volume between 'Río Copiapó en La Puerta' and 'Río Copiapó en Angostura' gauges. The reference (null) volume corresponds to 1973. Source: adapted from DGA (2013).

Table 1. Water rights given to the different water use sectors and estimated current demands.

Water use sector	Water rights given (m^3/s)	Current water demand (m^3/s)
Agriculture	10.00 (56.4%)	5.07
Mining	3.05 (17.2%)	0.398
Potable water	1.56 (8.8%)	0.525
Other industries	0.067 (0.4%)	0.033
Unknown and not used	3.04 (17.2%)	–
Other uses	0.03 (0.2%)	–
Total	17.754	6.027

energy is involved not only for pumping but also for the water treatment using reverse osmosis (RO). The productivity of water for crop irrigation in terms of the contribution to GDP is quite low (i.e. 2.14% of the Atacama region annual GDP, i.e. US$4.15 billion in 2011) (Banco Central de Chile, 2013). Thus, the productivity of this water is approximately US$17.5 million/$m^3$/s. On the contrary, the mining sector produces the 48% of GDP, which implies a productivity of about US$5 billion/$m^3$/s (i.e. 285 times larger).

Due to acute water scarcity in the basin, new non-conventional water resources are being used in Copiapó. In a pioneering initiative in Chile, the wastewater treatment plant downstream of Copiapó started selling 0.125 m^3/s of reclaimed water to the main copper mine in the basin (Candelaria) and 0.05 m^3/s to a nearby iron mine. This water is pumped for about 30 km across a gradient of about 300 m. In addition, Candelaria is also pumping about 0.4 m^3/s of desalted water through an about 100-km-long pipeline from sea level to about 700 masl, which can eventually increase up to 0.5 m^3/s. These changes have reduced from about 0.4 to about 0.004 m^3/s the water pumped from groundwater by

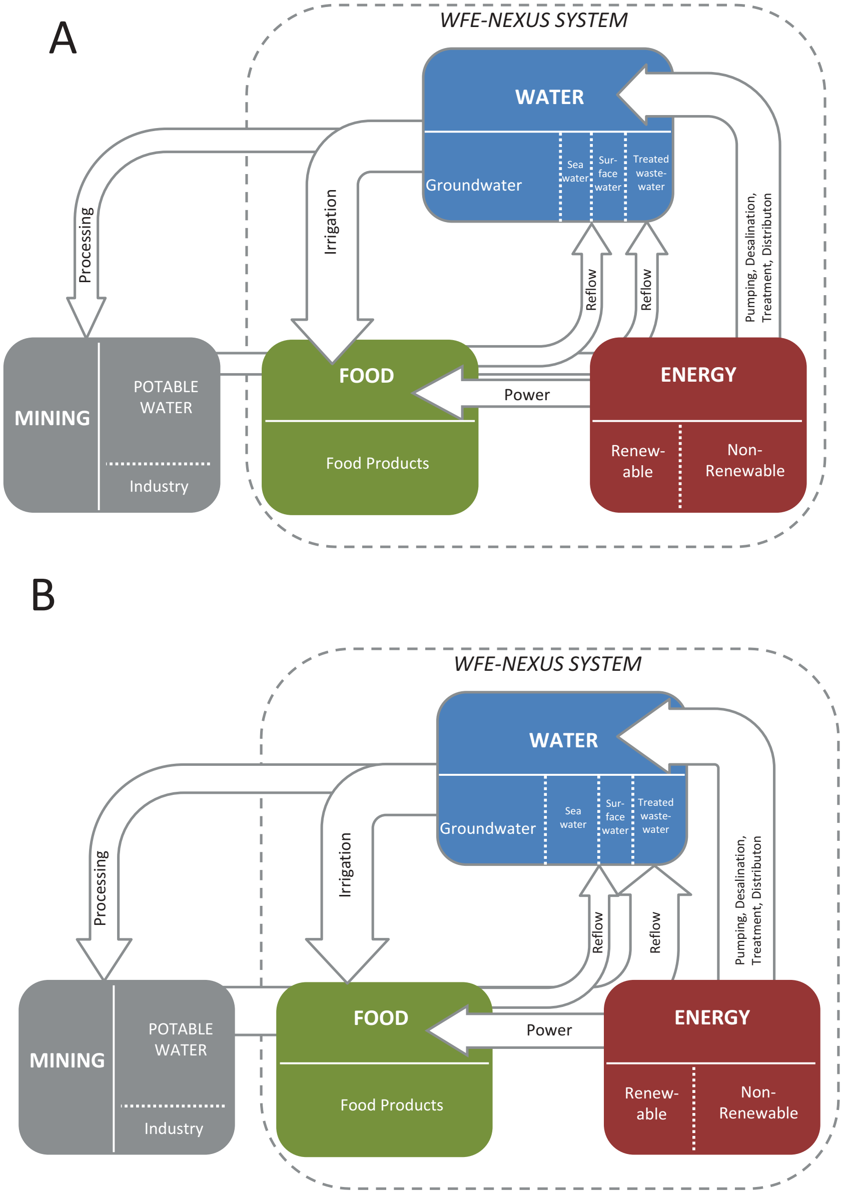

Figure 6. WFE nexus in the Copiapó region. Current and future conditions are depicted in the upper and lower panels respectively.

this mine. Thus, current water use in the basin implies a large energy use to pump water from the aquifer, and to desalt and pump seawater to the mine, which in turns means significant costs. For example, Brantes (2010) estimated the investment cost of the desalination plant implemented by the Candelaria mine as US$254 million.

Figure 6a illustrates the current status of the WFE nexus in the basin. A large amount of water is being used for irrigation. For this water to be available, energy is needed to pump water from the aquifer. Furthermore, more energy is needed to pump water from the sea as well as from the wastewater plant to reuse reclaimed water. Finally, drinkable water production requires energy for pumping and RO. Note than in the case of this basin, seawater is relevant for the overall water balance. Significant efforts must be made to develop a more sustainable management of the basin, in which the level of vulnerability under increasing population, a reduction in precipitation and higher temperatures should be reduced. This effort will clearly require larger uses of energy. Suárez et al. (2014) estimated a cost of US$781 million and energy requirements in the order of 4702 GWh to eliminate an expected water deficit of 527 Mm^3 (i.e., 0.48 m^3/s) between 2008 and 2042. The estimated energetic requirements only accounted for driving seawater RO and pumping this water to the city of Copiapó. The authors calculated a water quantity-based estimate of the water footprint associated with energy production and conversion, defined as the amount of water used to produce a unit of energy (Lazarova, Choo, & Cornel, 2012). By using water footprint values ranging from about 1 to 3 l/kWh typical of conventional coal combustion (Lazarova et al., 2012), a total water footprint ranging between 0.1 and 1.4×10^6 m^3 was estimated for these management options.

Figure 6b illustrates the potential future status of the WFE nexus in the basin due to global change. Note that not only future challenges but also major current deficits must be addressed. Given the recent experience of the mining sector, seawater is likely to become a significant part of the water budget in the basin, which in turn will mean an increase in energy requirements. The use of reclaimed water may increase even further as wastewater from small residential areas could also be included in the ongoing reuse scheme. Pressure on groundwater (and the energy used for pumping) will increase if no actions are taken to regulate its use. Moreover, it is uncertain whether the additional contribution of desalted seawater to the basin will motivate the unregulated growth of the areas dedicated to crops, or a more regulated recovering of groundwater levels. Finally, from the point of view of energy sources, because coal plants are easier to build and become operational in a shorter time, the WFE nexus could eventually move towards more complex and carbon-intensive alternatives.

WFE nexus in the Maipo region

The Metropolitan Region of Chile contains Santiago, the capital with a population of almost 6 million inhabitants (one-third of Chile's total population). Industry, commerce and financial services along with a small but export-oriented agriculture sector generate almost 40% of GDP.

This region has a Mediterranean climate. Mean temperatures range from 20°C in summer to 10°C in the winter season. Mean annual precipitation reaches 280 mm, being concentrated in the fall and winter seasons (May–August). Snow accumulation occurs above 1500 masl during winter. A significant El Niño effect on its precipitation regime has been reported (Aceituno, 1988). Since total evaporation reaches 1800 mm, irrigation is fundamental for the development of agriculture in the valley.

The Maipo River runs from the peaks of the Andes (Volcan San Jose, 5848 m) towards the Pacific Ocean, with an extent of 250 km. It has been divided into three major sections for administrative purposes. Average annual flow in the first section is about 100 m^3/s (DGA 2003), with highest seasonal flows of 220 m^3/s observed in January. The Maipo River supplies more than 70% of the total demand for irrigation in the basin and up to 90% of the residential demand for drinking water.

Studies made by the Directorate General of Water (DGA) (2003) indicate that permanent water-use rights have already been granted. Only a few contingent water-use rights allow the development of new irrigated agricultural areas in the basin.

Because of the location (central valley) and size of the capital, there is potential direct competition between urban and agricultural sectors. Irrigated agriculture is the main water user in the basin, covering an area of 136,000 ha. However, irrigation efficiency is considered to be low (approximately 50%) due to the predominance of furrow irrigation which leads to high water losses. Per capita water use has a mean value of 150 l/day (617 l/day in high-income areas). According to the records of the main water utility company, the city's water demand is approximately 20 m^3/s.

The impacts of climate change on water resources in this region have been documented. There is a consensus among GCMs that this region will experience a reduction in total annual precipitation. As a consequence, reduction in the magnitude of flows in the Maipo River is expected. Meza, Vicuña, Jelinek, Bustos, and Bonelli (2014) used a hydrological model run under two different SRES scenarios (i.e. emissions scenarios obtained from the Special Report on Emission Scenarios of the IPCC(Nakicenovic and Swart, 2000)) and three GCM climate projections and determined that peak flows can be reduced by up to 40%. Advancement in the centre mass of the hydrograph was also detected. As a consequence of the reduction in the magnitude of river discharges and changes in peak seasonality, the reliability of water-use rights will change. Existing water rights will not yield the originally designed flow to users; this could generate impacts on agricultural production and/or lead to more intense competition for water resources with the urban sector (Meza et al., 2012).

Urban areas are not as sensitive as agriculture, although some problems of coverage can be detected (Meza et al., 2014). As no new permanent water rights can be granted, the only available options for agriculture will be to improve efficiency (increasing the participation of pressurized systems such as drip irrigation) and/or increase the use of groundwater.

Figure 7 shows current and future conditions for the WFE nexus. The urban element is outside of the system but it exerts a strong influence in the behaviour of the WFE nexus as the city demands a substantial fraction of surface water resources in the upper section of the basin. Because of the level of intensification, agriculture in the region demands energy for power (i.e. tractor and other machineries) and uses fertilizers. Under global change scenarios the WFE nexus will become more complex, not only because of increasing competition among urban and agriculture but also because the Maipo has the potential for hydropower generation which will be exploited in the next few years.

WFE nexus in the Maule region

The Maule River Basin is located between latitudes 35º05′ and 36º30′ S in central Chile, with an area of 20,295 km^2. In terms of population there are two major cities in the catchment: Talca, the regional capital with 238,800 inhabitants, and Linares, with 100,600 inhabitants.

The basin exhibits a Mediterranean climate with mean temperatures ranging from 8°C in winter to 22°C in summer, and mean annual rainfall of 700 mm observed in Talca, with most part of the wet season in winter, as for most of the Chilean Mediterranean basins. The Maule, the main river in the catchment, is born in the header of the catchment at the most important reservoir of the basin, Maule Lake at 2170 masl and ends in the Pacific Ocean, with a length of 250 km. This natural reservoir was intervened in 1947, after the irrigation Agreement Riego-ENDESA between the Irrigation Board and the main electric

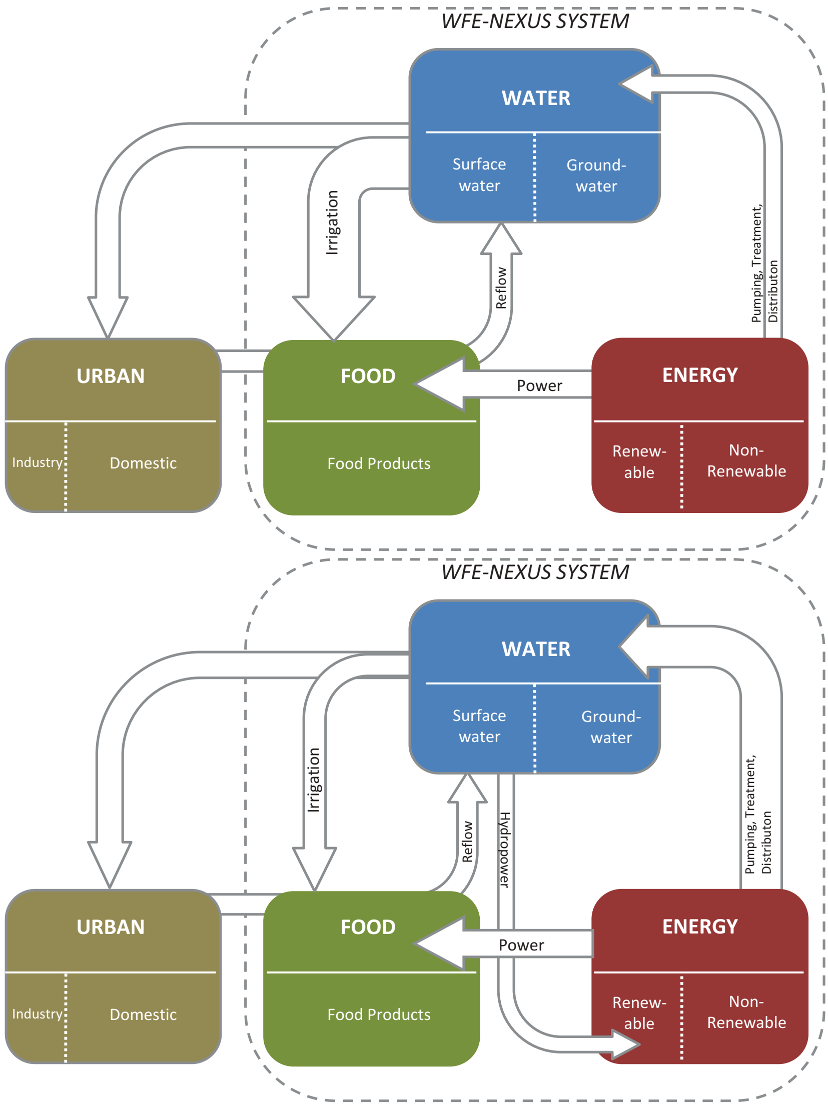

Figure 7. WFE nexus in the Maipo region. Current and future situations are depicted in the upper and lower panels respectively.

company of the country to increase its capacity to a maximum of 1420 Mm^3. The reservoir holds water for both hydroelectric and irrigations purposes and it is controlled by the Hydraulic Works Department (Dirección de Obras Hidráulicas), part of the Ministry of Public Works. Water use from Maule Lake is regulated under the Water Code (1981) and several public laws and writs such as Convenio 1947 issued by Dirección General de Aguas in 1983.

The upper part of the basin its characterized by its steep topographical gradient, with heights ranging from 500 to almost 4000 masl in just 100 km. As in most part of central Chile, these watersheds are generally snowmelt dominated, with most of their peak stream flow in late spring and the summer months, September–January. Land use is predominantly bare and rocky soil because of its mountainous nature with only a small number of human settlements and no intensive agriculture. This area has six hydropower stations, four run-off schemes and two with reservoirs, but with limited regulatory capacity as the purpose of their dams is to increase the water elevation.

The important Embalse Colbún (Colbún Reservoir) separates the higher lands from the flat plains, with 154,400 m^3 of storage capacity. The construction of this reservoir was finished in 1985. It stores water to generate energy through the Colbún and Machicura power stations (400 and 50 MW). Five other run-off power stations also exist on irrigation canals over the region, adding up to 1479.7 MW of installed capacity in the catchment.

The middle part of the catchment presents mild to flat slopes where agriculture develops vastly, composed of several small farmers and some agro-exporter producers that in turn are grouped in farming and irrigation associations. The use of water from the Maule River and from reservoirs is regulated by the Junta de Vigilancia del Río Maule (JVRM), or Vigilance Board of the Maule River, an institution developed under the current Water Code in Chile and which is formed by persons or institutions who possess water rights, although historically it has been mainly controlled by farmers (Bauer, 2009).

In the Maule basin, farmers and hydropower companies have conflicting demands over water uses: agriculture wants to store water during the rainy winter to use during the growing season in the warm and dry summer, while hydropower companies want to store during the summer when the river is at maximum due to spring and summer snowmelt and use it for higher electricity demands times in winter (Bauer, 2009). During the last big droughts (1998–99) and recently (2012) there have been several conflicts about how to manage water stored in different reservoirs in the catchments. Farmers occupied several public buildings in the regional capital, Talca, to protest against actions taken by a hydropower company.

Irrigation in Chile supplies 40% of cultivated land and gives security to high-value products for export and also represents around 70% of water consumption. In the Maule River Basin the main crops grown are cereals, fruit trees and pasture.

In 2014, the two major hydropower companies in Chile agreed to be part of the JVRM in order to regulate the use of waters in the basin. Although their participation is not yet official, it is seen as a first step in the integration between different users in one of the most important basins in the country in terms of energy and food production, with its implicit use of water.

In terms of drivers that could affect the current relationships between actors and their behaviour towards water use, climate change is a major one. Previous works (CEPAL, 2009) project a reduction in rainfall in central Chile that could led to a fall in discharge by up to 40% and an increase in temperatures that could accelerate the snowmelt in snow-dominated basins like that of the Maule River, changing the yearly water cycle. Such future climate change scenarios will intensify competition for surface water resources and will induce farmers to exploit groundwater resources. Figure 8 illustrates this situation under the WFE nexus framework used here. Note how the sizes of the arrows have been modified in the global change scenario to represent the impacts of competition on food and energy security. It is expected that hydropower generation will be affected as a direct consequence of reduced streamflows. In addition, groundwater, especially for agriculture, becomes a rather obvious alternative to cope with increasing climate variability and competition with other sectors.

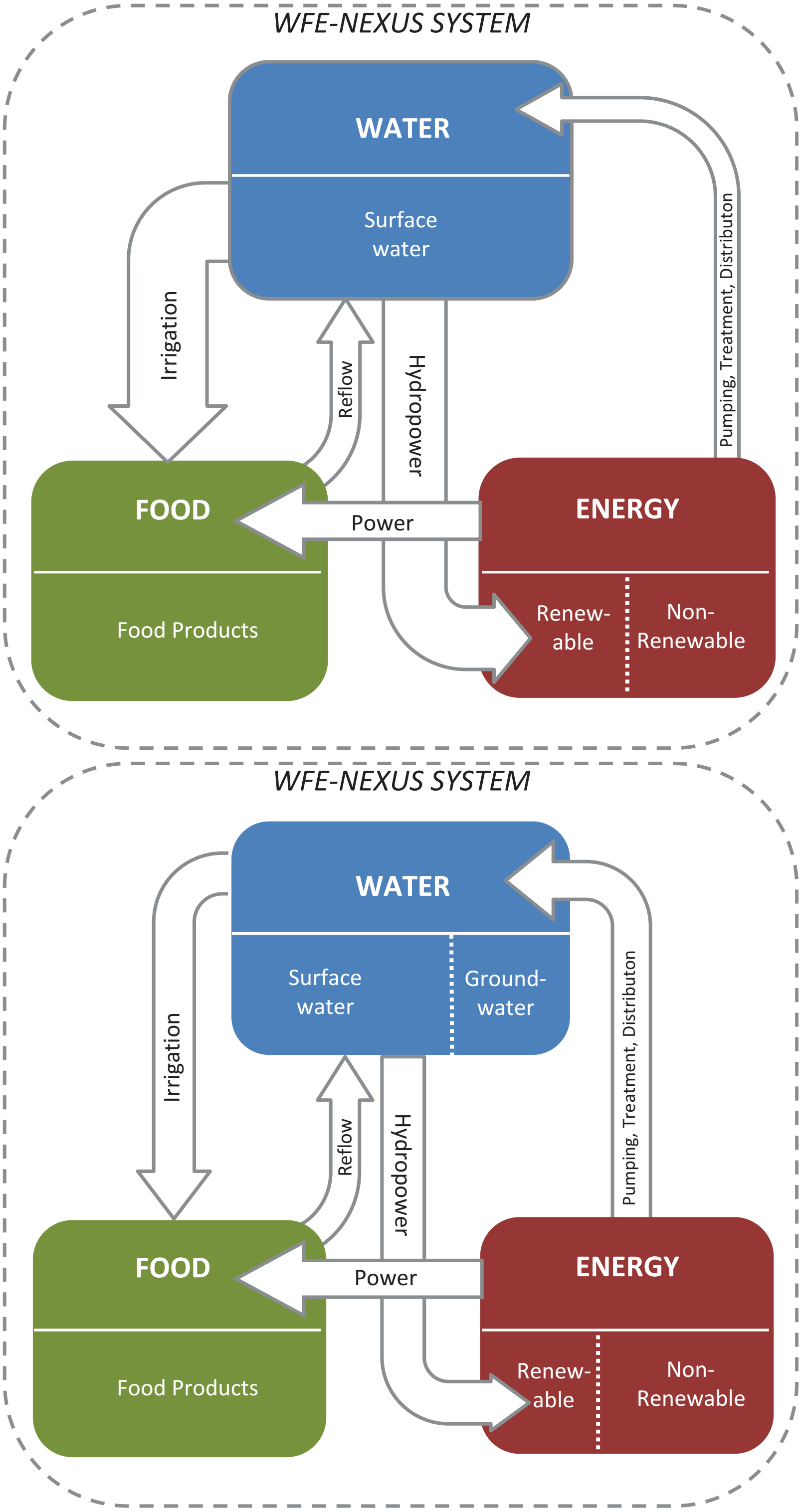

Figure 8. WFE nexus in the Maule region. Current and future situations are depicted in the upper and lower panels respectively.

Conclusions

New opportunities to ensure water–food and/or energy security arise from the integrated analysis about the WFE nexus. In this work we have presented a conceptual framework that focuses on the relationships between systems, particularly the influence and provision of resources. This framework can be used to assess the influence of global change drivers, communicating impacts or consequences as changes in the direction and magnitude of the flows, as well as increasing its complexity (new relationships emerge). No adaptation measurements have been included in the framework. However, the framework is flexible enough so that one could evaluate the impact and effectiveness of adaptation strategies by evaluating the modifications in the WFE nexus.

We have presented four case studies to illustrate its applicability and evaluated them comparatively under the most likely global (climate) change scenarios. With regards to the regions analyzed, the following specific remarks can be made:

- The Antofagasta region has two peculiar conditions that shape a current active water–energy nexus: high copper ore yields and extreme aridity. This nexus should be enhanced in future due to heavy reliance on water desalination as the main source of water for both copper production and human consumption.
- The Copiapó region represents an example of a highly active WFE nexus under pressure due to the intensive exploitation of water resources and the use of groundwater resources.
- The Maipo region corresponds to a case in which the WFE nexus is conditioned by strong competition from the urban sector that will likely intensify with climate change.
- The Maule region is an example of a WFE nexus in which water is at the cornerstone of the system, delivering surface resources to support agriculture and hydropower generation.

The application of this framework for the case studies allow us to extract the following conclusions:

- The full integration of water and sustainable energy is required to provide solutions for water shortages observed in highly vulnerable basins located in arid environments in Chile. In such environments, reuse and recycling as well as desalination are becoming attractive management options, although their impacts and negative externalities must be well characterized and understood by decision-makers, water and energy managers, and society.
- Comprehensive watershed models able explicitly to take into account energy and water fluxes as well as irrigation practices are required to develop strategies, policies and adapting capacities to overcome unsustainable water uses. These models must consider surface–subsurface interactions, and represent several aspects of water resources planning and management, land-use change and elements of environmental and social vulnerability.
- Coordination of stakeholders and water users is fundamental when adapting strategies and policies oriented to strengthen the WFE nexus approach. Private entities with particular goals and a restricted vision can limit this approach, particularly under a weak governance of the resources.

- As the WFE nexus concept continues to evolve, new conceptual frameworks will be necessary to accommodate complex and dynamic relationships among systems. In this case, a quantitative model has to be implemented so the nature of the interactions and the potential conflicts can be assessed in a more realistic manner.

Acknowledgements

The authors are grateful for the valuable contributions made by Eduardo Bustos (figures) and Andrés Pica (data processing in the Antofagasta case).

Funding

This work was carried out with the aid of a grant from the Inter-American Institute for Global Change Research (IAI) [grant number CRN3056], which is supported by the US National Science Foundation [grant number GEO-1128040]. In addition, several collaborative ongoing projects have provided support for research presented in different sections. The authors would like to acknowledge funding from the FONDEF [grant number D10I1051], the European Union Seventh Framework Programme (FP7/2007-2013) [grant agreement 283025 to Project COROADO], and the Centro de Desarrollo Urbano Sustentable [CEDEUS Conicyt/Fondap/15110020].

References

Aceituno, P. (1988). On the functioning of the Southern Oscillation in the South American sector. Part I: Surface climate. *Monthly Weather Review*, *116*, 505–524. doi:10.1175/1520-0493(1988)116<0505:OTFOTS>2.0.CO;2

Banco Central de Chile. (2013). *Cuentas Nacionales de Chile, PIB regional 2012*.

Bauer, C. (2009). Dams and markets: Rivers and electric power in Chile. *Natural Resources Journal*, *49*, 583–651. ISSN: 00280739.

Brantes, R. (2010). *Minería del Cobre y Recurso Hídrico*. Santiago, Chile: XIV Jornadas Conaphi-Chile.

Comisión Económica para América Latina y el Caribe (CEPAL). (2009). *La economía del Cambio Climático en Chile* [The economy of Climate Change in Chile]. Retrieved from. http://www.cepal.org/publicaciones/xml/0/47220/La_economia_del_cambio_climatico_en_Chile_Completo.pdf

Dirección General de Aguas (DGA). (2003). *Evaluación de los Recursos Hídricos Superficiales en la Cuenca del Río Maipo*. Santiago, Chile: DGA.

Dirección General de Aguas (DGA). (2013). *Actualización de la Modelación Integrada y Subterránea del Acuífero de la Cuenca del Río Copiapó: Informe Final S.I.T. Nº 332*. Santiago, Chile: DGA.

División de Ingeniería Hidráulica y Ambiental, Pontificia Universidad Católica de Chile (DICTUC). (2010). *Análisis Integrado de Gestión en Cuenca del río Copiapó*. Santiago, Chile: DICTUC.

Falvey, M., & Garreaud, R. (2009). Regional cooling in a warming world: Recent temperature trends in the SE Pacific and along the west coast of subtropical South America (1979–2006). *J. Geophys. Res*., *114*, 1–16.

Finley, J. W., & Seiber, J. N. (2014). The nexus of food, energy, and water. *Journal of Agricultural and Food Chemistry*, *62*, 6255–6262. doi:10.1021/jf501496r

Fuenzalida, H., Aceituno, P., Falvey, M., Garreaud, R., Rojas, M., & Sanchez, R. (2007) Study on Climate. Variability for Chile during the 21st century. *Technical Report prepared for the National Environmental Committee* (in Spanish). Retrieved from: http://www.dgf.uchile.cl/PRECIS

Hayhoe, K., Cayan, D., Field, C. B., Frumhoff, P. C., Maurer, E. P., Miller, N. L., . . . Verville, J. H. (2004). Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences of the United States of America*, *101*, 12422–12427. doi:10.1073/pnas.0404500101

Haylock, M. R., Peterson, T. C., Alves, L. M., Ambrizzi, T., Anunciação, Y. M. T., Baez, J., ... Vincent, L. A. (2006). Trends in total and extreme South American rainfall 1960–2000 and links with sea surface temperature. *Journal of Climate*, *19*, 1490–1512. doi:10.1175/JCLI3695.1

Lazarova, V., Choo, K., & Cornel, P. (2012). *Water–energy interactions in water reuse*. London, UK: IWA Publ.

Luckman, B. H., & Villalba, R. (2001). Assessing the synchroneity of glacier fluctuations in the western Cordillera of the Americas during the last millennium. In V. Markgraf (Ed.), *Interhemispheric climate linkages* (pp. 119–140). London: Academic Press.

Meza, F., Wilks, D. S., 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. doi:10.1061/(ASCE)WR.1943-5452.0000216

Meza, F. (2013). Recent trends and ENSO influences on droughts in Northern Chile: An application of the Standard Precipitation Evapotranspiration Index. *Weather and Climate Extremes*, *1*, 51–58.

Meza, F. J., Vicuña, S., Jelinek, M., Bustos, E., & Bonelli, S. (2014). Assessing water demands and coverage sensitivity to climate change in the urban and rural sectors in Central Chile. *Journal of Water and Climate Change*, *5*, 192–203. doi:10.2166/wcc.2014.019

Nakicenovic, N.and Swart, R. (Eds). (2000). *Special report on emissions scenarios*. Cambridge University Press, New York.

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. doi:10.1002/sd.v19.4

Ringler, C., Bhaduri, A., & Lawford, R. (2013). The nexus across water, energy, land and food (WELF): Potential for improved resource use efficiency? *Current Opinion in Environmental Sustainability*, *5*, 617–624. doi:10.1016/j.cosust.2013.11.002

Rosenbluth, B., Funzalida, H., & Aceituno, P. (1997). Recent temperature variations in southern south America. *International Journal of Climatology*, *17*, 67–85. doi:10.1002/(SICI)1097-0088(199701)17:1<67::AID-JOC120>3.0.CO;2-G

Suárez, F., Muñoz, J. F., Fernández, B., Dorsaz, J.-M., Hunter, C. K., Karavitis, C. A., & Gironás, J. (2014). Integrated water resource management and energy requirements for water supply in the Copiapó River basin, Chile. *Water*, *6*, 2590–2613. doi:10.3390/w6092590

Vicuna, S., Dracup, J. A., Lund, J. R., Dale, L. L., & Maurer, E. P. (2010). Basin-scale water system operations with uncertain future climate conditions: Methodology and case studies. *Water Resources Research*, *46*(W04505). doi:10.1029/2009WR007838