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Water Use and Climate Stressors in a Multiuser River Basin Setting: Who Benefits from Adaptation?

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Abstract
Adapting to new climate conditions will require an intricate mix of knowledge, planning, coordination, and foresight. There is increasing sectoral evidence on the implementation of successful adaptation actions. However, the success of these actions when we consider the interdependencies among sectors remains debatable. This paper aims to assess who benefits from implementing adaptation options in a multiuser river basin to both climate-induced and demographic stress on water use. Our analysis relies on a hydro-economic model that considers two sets of water users: agriculture and urban households. We innovate in our modelling approach by analyzing and explicitly integrating the household-level economic behavior through its water demand. We assess the cross-user consequences of autonomous and planned adaptation actions. We provide insights into the different trade-offs at the basin level, demonstrating the compatibilities and divergences between agriculture and household-level water demand. We found different consequences of implementing either autonomous or planned adaptation measures. For instance, a decentralized scheme would drive negative implications for the entire basin, although the less water-intensive sector will be better off. On the other hand, different policy interventions would drive positive consequences for the entire basin, with the most water-intensive sector benefiting the most. These results highlight the distributional consequences across users of different adaptation measures.

Keywords Water management · Climate change adaptation policies · Economic consequences · Trade-offs · Multiuser

1 Introduction

Demographic and climate-induced changes are expected to have severe consequences across countries and human groups (Hoegh-Guldberg et al. 2018). In this context, adaptation options

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Extended author information available on the last page of the article are essential to mitigate the adverse outcomes of these changes (de Coninck et al. 2018). Although there is increasing evidence on the implementation of successful adaptation options (Moser and Boykoff 2013), these could be hampered by behavioral barriers, market failures, policy distortions (Biesbroek et al. 2013; Masud et al. 2017; Moser and Ekstrom 2010), and the interdependencies among the different adaptation actions developed (Eisenack et al. 2014). Thus, adaptation success cannot be granted, especially where multiple sectors interact and compete for resources.

This study aims to understand who benefits from the implementation of adaptation options within a multi-sector perspective, aimed at providing insights on expected conflicts across users and livelihoods in both climate-induced and demographic stress context. Our analysis relies on a hydro-economic model (HEM) that considers two water users: agriculture and urban households. We analyze the agricultural sector using a farm model and the urban household sector through a household-level water demand, explicitly incorporating households' economic behavior on water use.

Agriculture is expected to be among the most affected sectors because of climate change, especially in terms of change in water availability, with significant socio-economic consequences (Nelson et al. 2009; Schleussner et al. 2016). Due to the changes in climatic conditions (e.g. temperature or precipitation), farmers are expected to adapt their practices. For instance, by changing the array of cultivated crops (Seo and Mendelsohn 2008; Shaffril et al. 2018), implementing water management practices (Elliott et al. 2014; Fader et al. 2016; Iglesias and Garrote 2015), or moving labor toward off-farm activities (Dasgupta et al. 2014; Fernández et al. 2019; Karfakis et al. 2012). Future climatic conditions are also expected to affect urban households' behavior, driving the implementation of adaptation options. These adaptation options could include migration (Castells-Quintana et al. 2018; McLeman and Smit 2006; McLeman and Hunter 2010) changes in energy (Auffhammer and Mansur 2014; Davis and Gertler 2015) and water demand (Ashoori et al. 2016; Parandvash and Chang 2016; Yates et al. 2013), among others. Evidence suggests that some of these adaptation strategies have been successful when evaluated from a single sector perspective. However, the success of these actions when we consider the interdependencies among sectors remains debatable.

These interdependencies are evident when we consider the use of water resources by both the urban and agricultural sectors. Currently, water resources face an unprecedented confluence of pressures from both humans and the environment (Wang et al. 2016), with agriculture and urban growth as the most relevant human-related stressors. Unfortunately, these pressures are expected to increase in the future, exacerbating the conflicts between water users (Flörke et al. 2018).

The literature on water resources concurs on the use of the river basin scale for the analysis of water resource management issues (Brouwer and Hofkes 2008; Harou et al. 2009). From the water use perspective, the spatial location of each water user within the river basin is relevant for water allocation. This is especially true in those settings in which water demand is satisfied through a cascading scheme, such as in many Andean basins that are characterized by steep slopes. Under this setting, the amount of water used by one user will impact the amount of water available for others downstream (Maneta et al. 2009b).

HEMs combine hydrologic and socio-economic information at the river basin scale, providing a systemic view aimed at assisting policymakers for water resource management. In general, the model aims to maximize the value for the whole basin, subject to different institutional, hydrological, and agronomic constraints (Harou et al. 2009; Hurd 2015).

The literature uses HEMs extensively—some applications include water conservation (Ali et al. 2020; Habteyes and Ward 2020; Liu et al. 2018), economic effects of water variability (Graveline et al. 2014; Maneta et al. 2009a; Torres et al. 2012), water quality (Gunawardena et al. 2018; Peña-Haro et al. 2011; Riegels et al. 2011), economic impacts of climate change (Esteve et al. 2015; Ponce et al. 2017; Varela-Ortega et al. 2013), and the water-food-energy nexus approach (Al-Riffai et al. 2017; Yang et al. 2016).

Mainstream literature on HEMs provides a detailed representation of both the hydrologic features of the basin and the agricultural sector. Some studies also include industry, environment, and the urban sector (Bekchanov et al. 2017; Brouwer and Hofkes 2008; Harou et al. 2009). To the best of our knowledge, no study analyzes the urban sector through the household-level water demand, thus, failing in the comprehensive assessment of the economics of water resources at the river basin scale.

Our study contributes to the literature in two ways. First, from a methodological perspective, we enrich the HEMs integrated framework by analyzing and explicitly integrating the household-level economic behavior through its water demand. Second, from a policy perspective, we use this enriched framework for the assessment of different adaptation options and the cross-user consequences of its implementation.

2 Material and Methods

The Vergara HEM (V-HEM) is a mathematical programming model designed to analyze different adaptation options and the consequences of its implementation on a multiuser basin. The model links users' economic behavior with the basin's hydrologic characteristics within a flexible and comprehensive framework. The model is aggregated at the municipality level and is solved using a modular approach (Braat and Van Lierop 1986).

The economic behavior of water users is analyzed using a combination of econometric and optimization methods. The household-level water demand model originates from a previous study (Rivera Bocanegra 2016) that computes the water demand using a discrete-continuous choice model, which allows considering increasing block rate prices (Hewitt and Hanemann 1995; Vásquez Lavín et al. 2017). On the other hand, agricultural water demand is modeled using a non-linear agricultural supply model, which is a mathematical programming model designed to evaluate the agricultural sector with high geographical disaggregation. It includes the main agricultural activities within the area and differentiates between water provision systems as rain-fed and irrigated (Ponce et al. 2014). The Basin hydrology is modeled using the soil and water assessment tool (SWAT;(Arnold et al. 1998)). The model's objective is to maximize the basin's total surplus, namely households' surplus and agricultural income.

2.1 Model Specification

Figure 1 presents the conceptual model. It shows that water available in each community (*FW*) depends on the water endowment, computed by the SWAT model (*DW*), and a water conveyance efficiency parameter (hd_u) for each user: hd_a for agriculture and hd_r for households. Under this setting, *FW* restricts the total amount of water that could be used by both households and farmers. Further, each community could use all the water available or leave some water (*WNU*) for the downstream community (dash line), in which case, the unused water in an upstream community will increase the water endowment downstream.

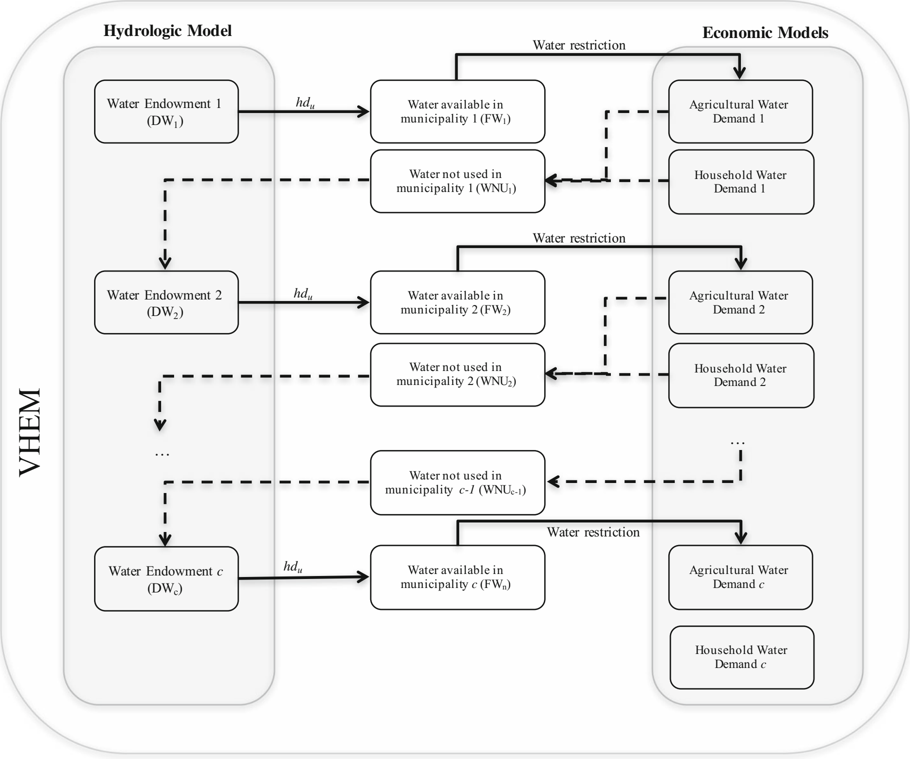


Fig. 1 Conceptual model

The household-level water demand originates from a previous study conducted in the same region (Rivera Bocanegra 2016). Through the benefit function transfer method (Johnston et al. 2015), it is possible to use this function to explain the benefits in other sites. The transfer of a parametrized function, allows us to adjust the transferred value according to several factors, such as socio-economic differences (house and inhabitants' characteristics). Residential water demand is presented in Eq. (1).

$$Ln(W_C) = \delta Z_c + \vartheta Ln(P^w) + \gamma Ln\left(\widetilde{y}_c\right) + \eta + \varepsilon \tag{1}$$

where W_c is the monthly household water demand in commune c; Z_c is a matrix containing household features and climatic variables (i.e., house characteristics, number of inhabitants, and temperature) that are thought to shift demand in commune c; P^w is the marginal water price faced by households; $\widetilde{y}_c$ is the monthly income adjusted by the Nordin difference (Nordin 1976); η is specified to capture the unobserved preference heterogeneity; ε captures the optimization error derived from the discrepancy between optimum and observed water consumption; and $\delta,\ \vartheta,\gamma$ are the parameters to be estimated. We assume that urban water demand will increase when temperature increases (Espey et al. 1997; Olmstead et al. 2007; Sebri 2014). Using the parameters estimated in (1), it is possible to compute the consumer surplus (*CS*) (details in supplementary materials). This is represented in Eq. (2).

$$CS = 12* \sum_{c=1}^{C} \left(\frac{P^w * W_{c1}}{\vartheta_c + 1} - \frac{[(PV_c - P^w)(W_{c1} - W_{cc})]}{2} \right) * H_c \tag{2}$$

In (2), the first component $\left(\frac{P^w * W_{c1}}{\vartheta_c + 1}\right)$ represents the consumer surplus, assuming that urban households will get all the water that they need, while the second component represents the effect of water competition between users $\left(\frac{[(PV_c - P^w)(W_{c1} - W_{cc})]}{2}\right)$.

Famers' surplus (FS) is represented in Eq. (3), in which $X_{c,\ a,\ s}$ denotes the area devoted to activity (crop) a in community c using system s (rain-fed or irrigated), $AC_{c,\ a,\ s}$ is the vector of average costs per unit of activity a in community c using system s, p_a is the price of activity a, and $y_{c,a,s}$ is the yield per hectare of activity a in community c using system s.

$$FS = \sum_c \sum_a \sum_s \left(y_{c,a,s} * p_a - AC_{c,a,s} \right) * X_{c,a,s} \tag{3}$$

The basin objective is to maximize the total surplus (TS), as shown in Eq. (4), subject to resource constraints as depicted below.

$$Max : TS = CS + FS \tag{4}$$

Equation (5) represents the calibrated cost function ($AC_{c,\ a,\ s}$), wherein the cost function parameters ($\alpha_{c,\ a,\ s}$ and $\beta_{c,\ a,\ s}$) are derived from a profit-maximizing equilibrium using Positive Mathematical Programming – PMP– (Blanco et al. 2008; Howitt 1995; Howitt et al. 2010).

$$AC_{c,a,s} = \alpha_{c,a,s} * \left(X_{c,a,s} \right)^{\beta_{c,a,s}} \tag{5}$$

In Eq. (6), FW_c represents the water available in community c, which is equal to the crop irrigation requirements of activity a ($fir_{c,\ a,\ irr}$) multiplied by the land allocated to it, plus the yearly household-level water demand (W_c) in commune c multiplied by the number of households of each commune H_c.

Equation (7) shows that the water available in community c should be lower than or equal to the water endowment computed by the SWAT model plus the water not used in the upstream community (WNU_{-c}) multiplied by the conveyance efficiency of user u in commune c. Equation (8) illustrates that the water not used in community c is the difference between the water endowment and the water used in community c. Finally, Eqs. (9) and (10) show resource restrictions associated with both total land and irrigated land, respectively.

$$FW_c = \sum_a fir_{c,a,irr} * X_{c,a,irr} + 12 * \sum_c W_c * H_c \tag{6}$$

$$FW_c \le \left(DW_c + WNU_{-c} \right) * hd_{uc} \tag{7}$$

$$WNU_c = DW_c - \frac{FW_c}{hd_{uc}} \tag{8}$$

$$\sum_a \sum_s X_{c,a,s} \le tland_c \tag{9}$$

$$\sum_a \sum_{irr} X_{c,a,irr} \le iland_c \tag{10}$$

We simulate water users' responses to climate and demographic stressors. Climate stressors on water resources are simulated shocking the water availability computed by the SWAT model (DW_c). We develop an average scenario based on Chile's Third National Communication on Climate Change (MMA 2016), which provides the expected changes in both temperature and precipitation for the periods 2011–2030 and 1991–2010. The scenario was obtained from available changes in precipitation and temperature in the study area for CMIP5-RCP2.6 and CMIP5-RCP8.5. We also account for climate impacts on agricultural productivity, which is modeled as changes in the yield parameter ($y_{c,a,s}$), while the impact of climate variables on the household-level water demand is modeled through changes in the temperature parameter (Z_c). Finally, demographic stressors are modeled as population growth by changing the number of households in each commune (H_c).

We assess the cross-user consequences of autonomous adaptation actions, such as changes in the array of cultivated crops and household-level water demand, and planned adaptation actions, including supply (improvement in water conveyance efficiency for both users) and demand management (pricing policies in urban areas) actions.

2.2 Case Study and Data

The Vergara basin lies within two regions, namely, Biobío and Araucanía, and, it is the largest sub-basin of the Biobío basin, one of the most important river basins in Chile. This basin has an extension of 4260 km^2, comprising ten municipalities with a total population of almost 200,000 inhabitants. Meanwhile, the hydrologic cycle within the Vergara river basin is completely dependent on rainfall patterns. It exhibits large seasonal variability, that is, runoff peaks during July and low flows during the summer. Thus, any decrease in the rainfall patterns will lead to a decrease in water availability within the basin (Stehr et al. 2008).

Agriculture is the most relevant socio-economic activity, with more than 14,000 smallholders—an average farm size of 20 ha—distributed across the basin (INDAP 2014). In terms of activities, 52% of farmers allocate a portion of their lands to the main cereals (oats, maize, and wheat), legumes, and potatoes (Fernández et al. 2016). The basin also has 59,000 residential water users (households) distributed within the ten municipalities, which are served by ESSBIO, a private water utility.

The agricultural sector is represented by 11 activities, aggregated into two categories, crops (7) and fruits (4). The crops considered are oats (rain-fed), common beans (irrigated), maize (irrigated), potatoes (irrigated and rain-fed), alfalfa (irrigated), sugar beet (irrigated), and irrigated and rain-fed wheat. The fruits considered are cherries, apples, walnuts, and pears, all of them being irrigated activities. Crop production is concentrated in rain-fed wheat, followed by irrigated wheat, whereas the most representative fruit is apple.

The urban area of the basin includes 164,000 inhabitants, with an average size of 3.1 inhabitants per household. In general terms, the study site (Concepcion) has similar characteristics to the policy site (Vergara river basin), with the average monthly income slightly higher in Concepcion (details in Table SM1 in supplementary materials).

The main information used in the model (area, production, and yield) dates from the last National Agricultural Census (INE 2007), taking into account a disaggregation at the communal level. This information was updated for 2018 according to the information published by the Agrarian Policies and Studies Bureau (ODEPA 2018a). The information on costs per commune, activities, watering systems (irrigated, rain-fed), and the labor intensity is extracted from ODEPA (2010) and updated for 2018 using information from ODEPA (2018a). Prices were taken from the ODEPA website (ODEPA 2018b), while we used elasticities from previous studies for the model calibration (Britz and Witzke 2008; Foster et al. 2011; Quiroz et al. 1995).

2.3 Scenario Development

The simulated climate impact on water availability suggests a 34% reduction (average) in river flows, with a maximum 36% reduction in Traiguen, Angol, and Renaico and a minimum 31% reduction in Los Sauces and Mulchen (Fig. 2).

We assumed that agricultural productivity would decrease by 10% for rain-fed activities and by 5% for irrigated activities (MINAGRI-MMA 2013; Santibáñez et al. 2008). Our climate simulations indicate an expected increase in temperature (9%), a decrease in precipitation (by 15%), and—according to official projections (INE 2018)— an increase of 13% in the number of households. Regarding adaptation, the autonomous adaptation actions are defined endogenously by the model. For the planned adaptation actions, we assume a 15% improvement in water conveyance efficiency for the agriculture sector (supply management action), 10% decrease in a water leak in the urban pipeline (supply management action), and 30% increase in water prices (demand management action). Figure 3 shows a summary of both stressors and adaptation actions.

On the one hand, we modeled two stressor scenarios: (1) Only climate-related changes, and (2) Climate-related changes plus demographic changes. On the other hand, we modeled five planned adaptation scenarios (PASs): (1) Improvement only in agricultural water conveyance efficiency (PAS1), (2) Decline only in the water leak (PAS2), (3) PAS1 plus PAS2 (PAS3), (4) Change only in household water pricing (PAS4), and (5) Joint implementation of all the actions (PAS5). We conducted the assessment of the planned adaptation scenarios related to the second stressor scenario (climate-related changes plus demographic changes).

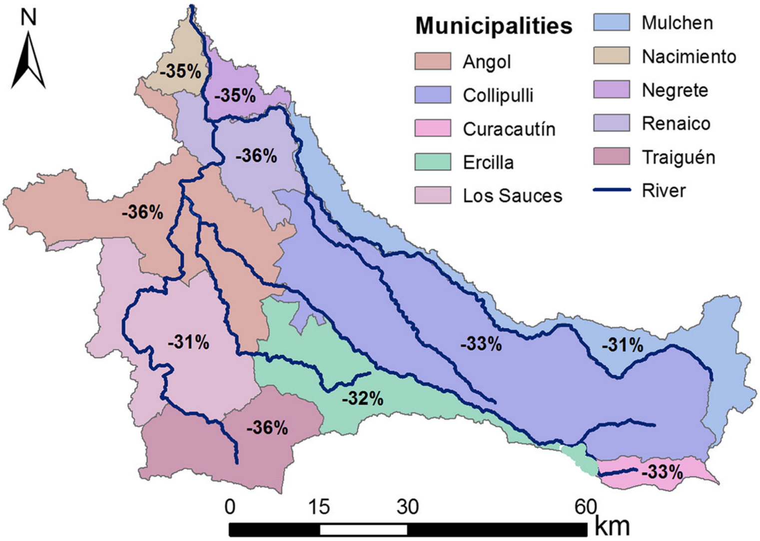


Fig. 2 Vergara River Basin: hydrological system and changes in water availability

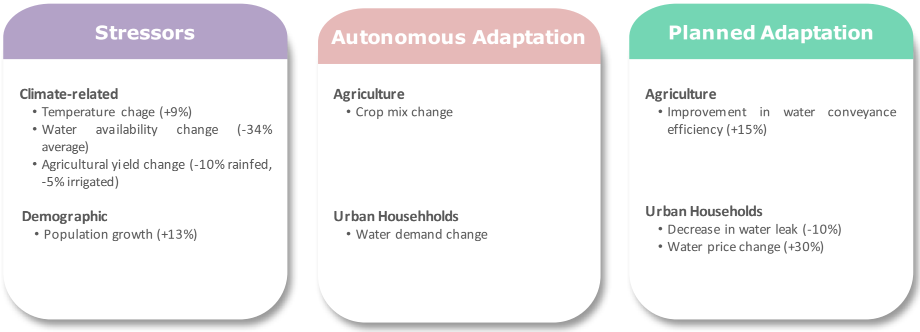


Fig. 3 Stressors and adaptation actions modeled

3 Results

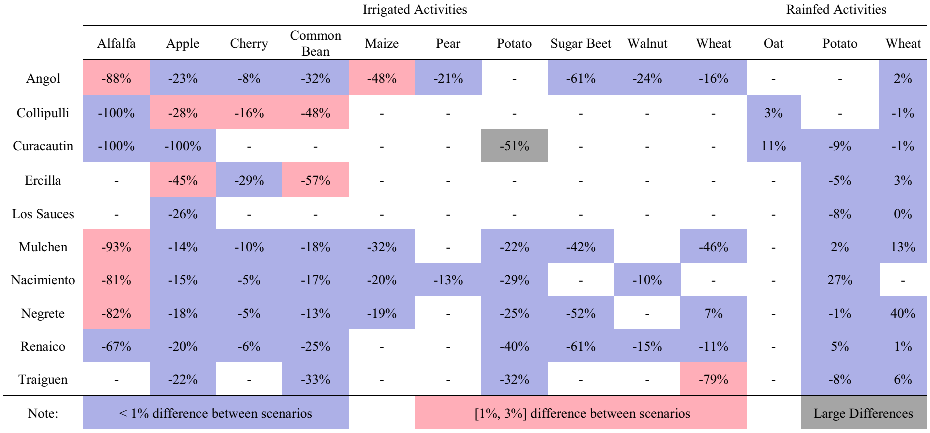
Under the different stressors, both water users (agriculture and households) should evaluate their water consumption decisions to allocate water to its most valuable use, in terms of economic welfare. Under this setting, the possibility of diverting water from one commune to the other is at the core of the basin's adaptive capacity. Due to this, different communes have different adaptive behaviors to meet not only their water demands (farmers and households) but also the demand of other communes downstream.

3.1 Autonomous Adaptation

We found that the user's autonomous responses depend on the specific stressor assessed, and the particular location of the water user within the basin. Adapting to the new conditions entails farmers changing their array of cultivated crops, with different results depending on the scenario analyzed. Under scenario 1, farmer's adaptation behavior—expressed as changes in their crop mix—would drive a 9% decrease (on average) in total agricultural land, which can be decomposed into a 9% increase in rain-fed land, and a 36% decrease in irrigated land. The adaptation actions are unevenly allocated within the basin, with Curacautin and Traiguen showing the largest change in irrigated land to adapt to this new climate condition (nearly 64% decline compared with the baseline). This result remains almost unchanged for most of the communes while considering scenario 2, but not for Curacautin, which reduces its irrigated land by 94% compared with the baseline.

The detailed changes in the array of cultivated crops under scenario 1 for all the communes show that the activities bearing the largest adaptation effort are alfalfa, sugar beet, and irrigated potato. Moreover, farmers in Curacautin adapt the most by decreasing their irrigated activities by the largest amount, with the land devoted to both alfalfa and apple decreasing by 100%, while land allocated to irrigated potato decreasing by 51%. Farmers complement this adaptation effort by decreasing land allocated to potato and wheat, whereas increasing land allocated to oat, all of which are rain-fed activities (Table 1). The change in the array of cultivated crops under scenario 2 is larger than under scenario 1, but with small differences between them. We use Table 1 to reflect these changes. For instance, cells in purple represent a difference between scenarios 1 and 2 of less than 1%, indicating that if land allocated to apple in Angol in scenario 1 decreases 23%, this decrease is greater than 23% but lower than 24% in scenario 2. The pink cells represent a difference between scenarios 1 and 2 within the range [1% to 3%],

Table 1 Autonomous adaptation: change on the array of cultivated crops (%)



	Irrigated Activities										Rainfed Activities		
	Alfalfa	Apple	Cherry	Common Bean	Maize	Pear	Potato	Sugar Beet	Walnut	Wheat	Oat	Potato	Wheat
Angol	-88%	-23%	-8%	-32%	-48%	-21%	-	-61%	-24%	-16%	-	-	2%
Collipulli	-100%	-28%	-16%	-48%	-	-	-	-	-	-	3%	-	-1%
Curacautin	-100%	-100%	-	-	-	-	-51%	-	-	-	11%	-9%	-1%
Ercilla	-	-45%	-29%	-57%	-	-	-	-	-	-	-	-5%	3%
Los Sauces	-	-26%	-	-	-	-	-	-	-	-	-	-8%	0%
Mulchen	-93%	-14%	-10%	-18%	-32%	-	-22%	-42%		-46%	-	2%	13%
Nacimiento	-81%	-15%	-5%	-17%	-20%	-13%	-29%	-	-10%	-	-	27%	-
Negrete	-82%	-18%	-5%	-13%	-19%	-	-25%	-52%	-	7%	-	-1%	40%
Renaico	-67%	-20%	-6%	-25%	-	-	-40%	-61%	-15%	-11%	-	5%	1%
Traiguen	-	-22%	-	-33%	-	-	-32%	-	-	-79%	-	-8%	6%
Note:	< 1% difference between scenarios					[1%, 3%] difference between scenarios						Large Differences	

meaning that if land allocated to alfalfa in Angol in scenario 1 decreases by 88%, this decrease is greater than 88% but lower than 91% in scenario 2. Finally, the grey cell represents potato farmers in Curacautin, where the land allocated to irrigated potatoes reduce by 51% under scenario 1 and 92% under scenario 2.

In a situation without competition for water resources, households' water demand would increase due to the temperature increase. However, households compete with agriculture for water; thus, they should adapt their behavior by decreasing their water demand from this desired situation. Under scenario 1, adapting to the new climate conditions implies a small decrease in water demand for almost all the communes (1.3% average decline) but not for Curacautin, which adapts its water demand reducing it by 9.6%. Under scenario 2, Curacautin decreases its water demand by 14.5%, whereas, for the other communes, the decrease in water demand remains unchanged (1.3% average). Moreover, Curacautin is the only commune for which the water demand decreases under both the scenarios, by 6.6% and 11.5%, respectively; whereas, for other communes, the water demand increases 1.9% (average) in comparison to the baseline (Table 2).

By considering the autonomous adaptation actions developed by both the agricultural sector and households, our results suggest that the burden of adaptation is faced by the agricultural sector, as it shows the largest changes in its behavior compared to the baseline. Within agriculture, irrigated activities are the engine of the adaptation efforts. This is more evident in Curacautin, Collipulli, and Los Sauces, where all the effort is assumed by the irrigated sector, as the rain-fed land remains almost unchanged in compared to the baseline. Moreover, Curacautin shows the largest decrease in both the land allocated to irrigated activities and the household-level water demand. This situation could be explained by the low adaptive capacity at the head of the basin, as this commune does not have the option of getting more water from an upstream commune.

At the basin level, the disaggregated changes described above will drive changes in the total water use in each sector. In agriculture, adapting to the new conditions by changing the array of cultivated crops will lead to a decrease in water use. Under scenario 1, the average decline is 42%—from 111.43 million m^3 to 69.90 million m^3, while under scenario 2, the decrease is 45% to 68.99 million m^3. In contrast, urban water use increases by 1.3% (from 8.16 million m^3 to 8.26 million m^3) in scenario 1, and 14% in scenario 2. These data suggest that population growth has a bigger impact than climate change on urban water use.

Table 2 Autonomous adaptation: household-level water demand (m^3/month)

Commune	Baseline	Water demand: W_{cc}	
		Scenario 1	Scenario 2
Mulchen	13.129	13.431	13.429
Nacimiento	12.910	13.184	13.183
Negrete	13.003	13.310	13.308
Angol	13.328	13.589	13.585
Collipulli	12.664	12.863	12.849
Curacautin	12.683	11.843	11.211
Ercilla	12.773	12.897	12.891
Los_Sauces	12.889	13.141	13.137
Renaico	13.063	13.354	13.352
Traiguen	12.921	13.174	13.170

The economic meaning of the physical changes described above is derived in terms of economic welfare. At the aggregated level, the total farmer's income decreases approximately by 15% under both scenarios—from 75.4 million to USD 63.7 million and USD 63.4 million, respectively.[1] At the commune level, six communes experience income declines between 20% and 30%, two communes witness income declines by less than 20%, and only one commune by more than 45% (Curacautin). Moreover, four activities— dry wheat, irrigated wheat, apple, and alfalfa—together account for 81% of the income decline (details in Figure SM − 1 in supplementary materials).

The consumer surplus increases under both scenarios compared to the baseline (USD 11.7 million), confirming that households are the biggest beneficiaries of the autonomous adaptation actions developed in the agricultural sector. Notably, the consumer surplus is larger in scenario 2 than in scenario 1: USD 13.6 million versus USD 12.11 million. Note that household-level water demand is smaller in scenario 2, and the number of households is larger, thereby, explaining this counterintuitive result.

The question then is who benefits from autonomous adaptation. At the aggregated level, the basin is worse-off, as, under both scenarios, the total surplus decreases compared to the baseline: 13% in scenario 1 and 11% in scenario 2. However, at the user level, the residential sector increases its welfare, whereas farmers' income decreases.

3.2 Planned Adaptation

For agriculture, the impacts of the planned adaptation options are negligible on the total agricultural land allocation (around 1% change). However, the differences in the array of cultivated crops are large among the planned adaptation options assessed. Moreover, the adaptation actions intended for the urban sector have a small effect on agriculture's autonomous adaptation actions in most of the communes.

The implementation of the PAS1 will benefit irrigated activities (20% increase in irrigated land, equivalent to 1441 ha), while reducing rain-fed activities (0.6% rain-fed land, equivalent to 362 ha), with the largest increases in Curacautin, Traiguen, and Mulchen (Table 3). In contrast, PAS2 has a marginal impact on the array of cultivated crops (excluding Curacautin), whereas the joint implementation of both measures (PAS3) will benefit irrigated activities

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[1] Exchange rate: 650 Chilean pesos (CLP$) = to 1 USD.

Table 3 Planned adaptation: change on the array of cultivated crops (%)

	PAS1		PAS2		PAS4		PAS4		PAS5	
Communes	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Angol	0%	7%	0%	1%	0%	8%	0%	0%	0%	8%
Collipulli	0%	13%	0%	2%	0%	15%	0%	1%	0%	15%
Curacautin*	0%	54%	0%	388%	0%	464%	0%	59%	0%	538%
Ercilla	−1%	14%	0%	1%	−1%	16%	0%	0%	−1%	16%
Los_Sauces	0%	8%	0%	1%	0%	9%	0%	0%	0%	9%
Mulchen	0%	28%	0%	1%	0%	29%	0%	0%	0%	30%
Nacimiento	0%	12%	0%	1%	0%	13%	0%	0%	0%	13%
Negrete	0%	12%	0%	1%	0%	13%	0%	0%	0%	13%
Renaico	0%	8%	0%	0%	0%	9%	0%	0%	0%	9%
Traiguen	-1%	48%	0%	5%	−2%	54%	0%	2%	−2%	55%
Average	−0.2%	20%	0%	40%	0%	63%	0%	6%	0%	71%

*: Changes in Curacautin, considering its absolute value are: 5 ha. (scenario 2), 8 ha. (PAS1), 25 ha. (PAS2), 29 ha. (PAS3), 8 ha. (PAS4), and 33 ha. (PAS5)

(18% increase in irrigated land, excluding Curacautin). The implementation of PAS4 has a marginal effect on the agricultural sector behavior (excluding Curacautin). Despite these aggregated figures, irrigated activities in Curacautin increase under all the planned adaptation options, with the largest impact being in the PAS5 scenario.

The impact of the planned adaptation actions on the household-level water demand is small. The PAS1 drives an increase of 0.1% (average), with Curacautin showing a small decrease (0.4%); PAS2 drives an increase of 0.6% (average) in households' water demand, with Curacautin showing the largest increase (4.6%); the results remain almost unchanged under PAS3 (0.73% average increase). As expected, in the face of a price increase (PAS4), all the communes adapt their behavior by decreasing their households' water demand (2.6% in average), whereas the joint implementation of all the planned actions (PAS5) reduces the water demand marginally (Table 4).

At the aggregated level, due to the change in the array of cultivated crops, the total farmer's income shows a slight increase within the range [0.1% to 3%] depending on the scenario analyzed. In one extreme, under PAS4, farmers' income increase by 0.1%, equivalent to USD 58,000, while under PAS5, farmers' income increase by 2.55%, equivalent to USD 1.6 million. Moreover, the change on farmers' income is uneven across communes and scenarios analyzed (Fig. 4 Panel A).

As shown in Fig. 4 (Panel B), the impact on households' welfare is uneven, depending on the PAS implemented and the commune analyzed. Under PAS1, all the communes—except Curacautin, which decreases water demand—show a small increase in their water demands. This change drives a negligible increase in consumer surplus for those communes increasing their water demand, with an aggregated change of USD 2000. However, as Curacautin water demand decreases, its consumer surplus decreases, thus overcoming the positive impact of the other communes. The final result under PAS1 is a slight decrease in consumer surplus to USD 12,000. Under PAS2 and PAS3, the consumer surplus increases for all the communes. As expected, in the face of a price increase (PAS4), all the communes reduce their water demand, thus reducing the aggregated consumer surplus in USD 3.5 million.

The question then is who benefits from planned adaptation. As illustrated in Fig. 5, the basin is better-off in most of the planned adaptation scenarios (concerning scenario 2), with an increase ranging from USD 0.3 million to USD 5.3 million. Unlike autonomous adaptation, the consequences at the user level depend on the implemented action. Farmers increase their income when supply actions are implemented, while the impact on the residential sector is negligible. Meanwhile, in the face of demand management actions, households are worse-off,

Table 4 Planned adaptation: household water demand (% change)

Commune	PAS1	PAS2	PAS3	PAS4	PAS5
Mulchen	0.1%	0.1%	0.2%	−2.9%	−2.8%
Nacimiento	0.1%	0.1%	0.2%	−2.9%	−2.8%
Negrete	0.1%	0.1%	0.2%	−2.9%	−2.8%
Angol	0.1%	0.1%	0.2%	−2.8%	−2.6%
Collipulli	0.5%	0.2%	0.6%	−2.7%	−2.3%
Curacautin	−0.4%	4.7%	4.6%	−0.7%	3.7%
Ercilla	0.3%	0.2%	0.5%	−2.7%	−2.2%
Los_Sauces	0.1%	0.1%	0.2%	−2.8%	−2.6%
Renaico	0.1%	0.1%	0.2%	−2.9%	−2.8%
Traiguen	0.1%	0.1%	0.2%	−2.8%	−2.6%

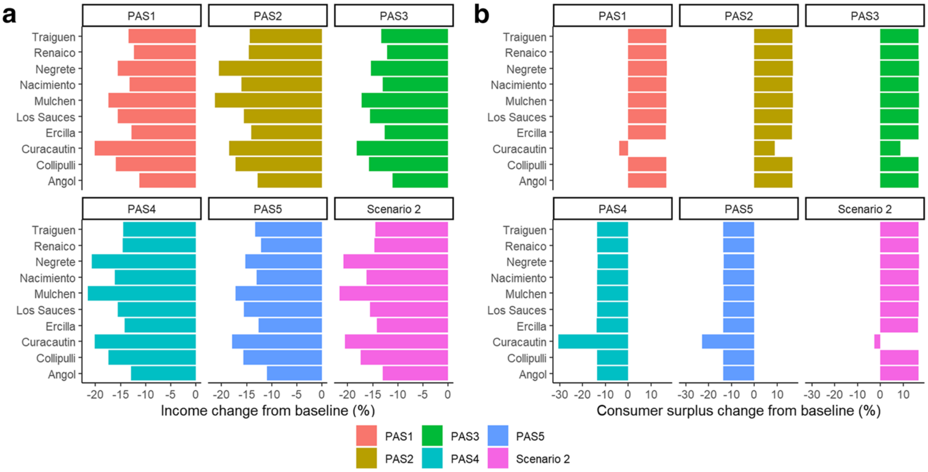

Fig. 4 Planned adaptation: farmers' income and household consumer surplus change (%)

and the impact on farmers' income is relatively small. Finally, when all the measures are jointly implemented, the agricultural sector is the one that benefits from planned adaptation.

4 Discussion

At the basin level, our results show that the autonomous adaptation efforts made by water users are similar, considering either climate-related stressors or multiple stressors. Under both scenarios, farmers adapt to those stressors by changing the array of cultivated crops, with large reductions in water-intensive activities. This result is in line with studies reporting changes in cultivated crops in favor of less water-intensive activities in the face of climate change (Fernández et al. 2019; Shaffril et al. 2018). In the face of both stressor scenarios, farmers and urban households are consistent in their autonomous adaptation actions. However, the action implementation is more intense in the case of the household sector, which increases its total water use by 14%. Our results show that

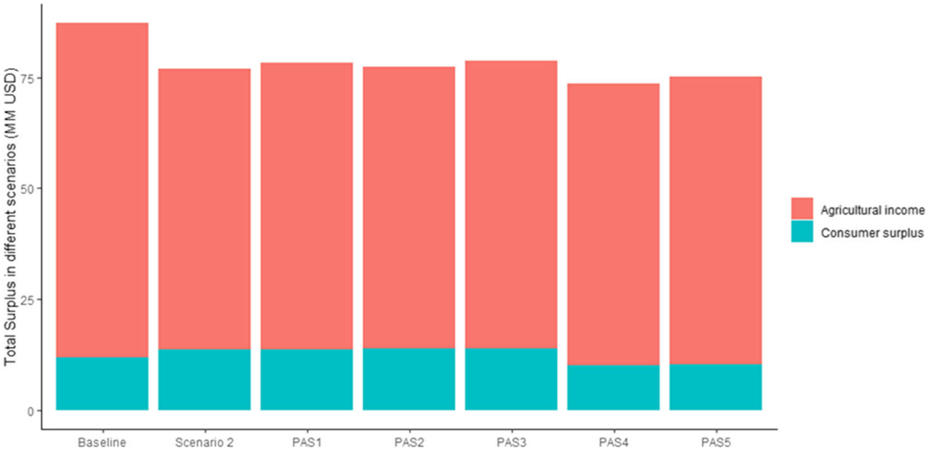

Fig. 5 Planned adaptation: total surplus change (USD million)

demographic stressors impose larger challenges to the urban water sector than climate change (Kuhn et al. 2016), highlighting the relevance of considering multiple stressors on the analysis of water resources (Ashoori et al. 2016; Vörösmarty et al. 2000).

The autonomous adaptation assessment shows that adaptation measures adopted in the agricultural sector tend to be more beneficial for the households' sector. Under both stressor scenarios, the change in the cultivated crop array leaves significant amounts of water available for the urban sector. At the same time, households do not reduce their water demand despite the reduction in water availability. Within a global framework, Flörke et al. (2018) also found that efficient water use in agriculture could free up water for the urban sector. Kuhn et al. (2016) and Mirchi et al. (2018) found similar results using the HEM framework. However, unlike them, we were able to account for the magnitude of the welfare changes at the household-level.

There is a growing body of literature addressing the priority of use for households in water competing settings (Flörke et al. 2018; Wimmer et al. 2015). Our results demonstrate that in the absence of intervention, the priority of use is granted to the households as they exhibit the largest water shadow price. It is expected that this result will hold in different contexts in which agriculture and households compete for water. However, this result might not hold if we include other sectors with larger shadow water prices, such as the manufacturing sector. (Ku and Yoo 2012; Vásquez-Lavin et al. 2020). In this case, a completely decentralized scheme that allocates water to its most valuable use could drive unwanted consequences at the household-level, such as water shortages.

From a policy perspective, the implementation of planned adaptation scenarios shows that the basin is better-off after its implementation. Regarding the beneficiaries, our results show that the isolated implementation of planned adaptation measures tends to target those for whom the measure is intended. For instance, the improvement in agricultural water conveyance efficiency is more useful for irrigated activities. In line with the studies assessing the consequences of improving the utility pipeline, a decrease in the water leak in the urban pipeline is beneficial to the households' sector (Molinos-Senante et al. 2016). As previous evidence shows, pricing policies in the urban sector would decrease the household-level water demand, acting as an adaptation measure in the face of water scarcity (Marzano et al. 2018; Olmstead and Stavins 2009). However, when the measures are jointly implemented, it seems that the most benefited sector is the agricultural sector.

The effectiveness of the adaptation actions depends on the free and decentralized exchange of water across communes and water users. In this sense, our framework mimics a perfect water market in which it allocates water to its most valuable use, as an enabling condition of any adaptation strategy (Bekchanov et al. 2015; Koopman et al. 2017). Using the HEM framework, Crespo et al. (2019) highlight that a well-functioning water allocation mechanism should also be socially acceptable to deliver the efficient results promised.

5 Conclusion

Using the V-HEM, we provide insights into the different trade-offs at the basin level, demonstrating the compatibilities and divergences between agriculture and household-level water demand. Moreover, employing the explicit modeling of the household-level water demand, we shed some light on the user's economic relationships, the interdependence across adaptation options, and on expected conflicts across users and livelihoods.

We found different consequences of implementing either autonomous or planned adaptation measures. On the one hand, a decentralized scheme would drive negative consequences for the entire basin, although the less water-intensive sector will be better off. On the other hand, different policy interventions would drive positive consequences for the entire basin, with the most water-intensive sector benefiting the most.

An *ex-ante* knowledge of the consequences and interlinkages of implementing different adaptation measures to deal with multiple stressors could foster the understanding on the socio-economic dimensions of global environmental change, aimed at informing policy designs to smooth those changes.

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Compliance with ethical standards

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