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The Economic Impacts of Climate Change at River Basin Scale: An agricultural-Residential Approach

“Los Impactos Económicos del Cambio Climático a Escala de Cuenca: Un Acercamiento Agrícola-Residencial”

Tesis para optar al grado de Magíster en Economía de Recursos Naturales y del Medio Ambiente

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ABSTRACT

Droughts and climate hazards are getting more and more common every day. This affects the environment and how people interact with it (i.e. water supply and changes in crop distribution given changes in crop production function requirements). This kind of events have economic consequences that change the surplus of economic agents such as households, farmers and industrial enterprises. Knowing the physical implications of these changes, this paper quantifies the economic effect of climate change and population patterns (among other factors), on the residential and agricultural sectors' welfare which need to change their behavior to optimize the use of an affected, such as water.

Keywords: Water, Agriculture, Households, Hydro-economic Models, Climate Change, Global Change, Vergara Basin, Chile.

1. INTRODUCTION

There has been a global, systematic increase on water demand in several sectors. The stress on water resources in activities as agriculture, land use and land use change, construction/management of reservoirs, emission of pollutants, and treatment of water pollution, among others (Bates, Kundzewicz, & Wu, 2008) is higher. Some of these rises are associated to weather patterns, while others are linked to interactions between human activities and the environment. Weather patterns are associated to climate change, including the decreasing of precipitations or the increase of extreme weather events (floods and droughts).

According to the conclusions of the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change, the future effects of the climate change over water resources will be uneven among sectors and regions (Field et al., 2014). The expected changes on water resources will increase the vulnerability of the main water users: farmers, households and industries. Agricultural activities are among the most important economic activities in developing countries, and the restrictions on water supply could affect the decision of farming, rearranging crop harvesting to maximize the economic value of the farm. Regarding residential demand, it is expected that households water demand will increase, due to climate change, but also due to the increase in population living in urban areas. Thus, any water shortage could have impact on the households' welfare.

Within this changing world, the challenge for policy makers is to develop new regulations/policies aimed at minimizing the expected losses within the water related sectors (Bekchanov, Sood, Pinto, & Jeuland, 2017). To accomplish this, policy assessment should include: i. the externalities associated to water use, ii. agents' behavior in the face of changes on water quantity/quality, and iii. the autonomous adaptation options that agents will take while facing these changing conditions. It is in this context is that Hydro-economic modeling rose allowing economists to address all these issues.

Hydro-economic models (HEMs) combine hydrologic and socioeconomic information aimed at maximizing an objective function (i.e. income, production), considering a set of constraints (i.e. resource and institutional). Most of the time these models are developed at river basin scale. There is a consensus on using the basin as an appropriate scale of analysis to study the management of water resources (UNCED, 1998). This scale is chosen because of the externalities associated to water mobility in which different water users are linked through the water system. In this context, HEMs allow to represent those interactions inside the basin thus combining hydrological and socioeconomic information (Harou et al. (2009), Bekchanov et al. (2017)).

There is extensive literature on HEMs including topics studies as: how to analyze water resources (Blanco-Gutiérrez, Varela-Ortega, and Purkey (2013), Ximing Cai, Ringler, and Rosegrant (2006), Varela-Ortega, Blanco-Gutiérrez, Swartz, and Downing (2011), Ward and Pulido-Velazquez (2008)), economic impacts of water variability (Graveline, Majone, Van Duinen, and Ansink (2014), Maneta et al. (2009), M. d. O. Torres et al. (2012)), water quality (Peña-Haro, Pulido-Velazquez, and Llopis-Albert (2011), Riegels (2011)), and the economic impacts of climate change (Hurd and Coonrod (2012), Jiang and Grafton (2012), You and Ringler (2010), Ponce, Blanco, and Giupponi (2014), Ponce, Fernández, Stehr, Vásquez-Lavín, and Godoy-Faúndez (2017)) among others.

Despite the large body of literature using HEMs, most of these studies consider only one sector (mostly agriculture), or include interactions with other sectors (as residential, industrial) but modeled as myopic agents that do not change their behavior while facing external shocks. This is why the main objective of this investigation is to quantify the economic impact of changes in water availability due to climate change at river basin scale considering an interaction between the agricultural and residential sectors, while competing for water consume. The literature gap is filled by modeling the interactions from an economic perspective in a comprehensive framework at basin scale. This means that our framework accounts for: i. the externalities associated to water use, ii. agents' behavior in the face of changes on water quantity/quality, and iii. the autonomous adaptation options that agents will take while facing these changing conditions. This competition considers water and temperature variability caused by climate change facing the agents to compete for water.

Given this analysis we can address public policies which aim to minimize the economic impacts of climate changes. We quantify the economic benefit of two different types of policies: improving agricultural conveyance efficiency and decreasing residential water leaks.

2. LITERATURE REVIEW

Brouwer and Hofkes (2008), Harou et al. (2009), and more recently Bekchanov et al. (2017) have conducted extensive reviews of most of the hydro-economic analyses, including advances and improvements along time, ways in which water can be modeled, estimation of the economic impacts of climate change, and how hydro-economic analysis are expected to be shaped in the future. This section presents a brief conceptual and empirical review of HEMs, focusing on the type of problems that were considered and how they approach them.

HEMs began in the 1960s and 70s in Israel and the United States with papers like Bear and Levin (1966). The “hydro-economic” name changed along time from hydrologic-economic, economic-hydrologic-agronomic, until it converged to today’s name. The popularity of these kind of models rose linked to the interest of water resource management analysis.

In general, HEMs are used to find the optimal resource allocation (land and water mostly), which maximizes the value (i.e. income, surplus) within a specific area or minimizes the loss of some climatic change. HEMs can be developed in two ways: modular or holistic (Brouwer & Hofkes, 2008). In the modular approach, the system (basin) is represented by different modules (hydrologic and economic), in which the information goes from one part to another of the model. A link is generated between the hydrological and economic model, in which the hydrologic module is used as input of the economic module, working separately. The holistic models consider the variables that are solved exogenously in the modular approach (i. e water supply, prices, yields) as endogenous variables in a related systems of equations (X Cai & Wang, 2006). Due to the complexity, and information requirements, associated to the holistic approach, most of HEM studies follow a modular approach based on basic relations between modules of the model.

As shown in Harou et al. (2009), HEMs have addressed a wide range of water resource problems in many locations around the world. Water resources can be differentiated by instream and off stream use. Referring to instream uses studies considered the generation of hydropower, navigation and recreation uses, while off stream cover consumption uses (directly or as an input for some activities, such as residential consumption and agricultural production respectively).

Table 1 presents information about the type of sectors analyzed by studies worldwide, while Graphic 1 shows the number of studies per sector.

Table 1: Hydro-economic Studies

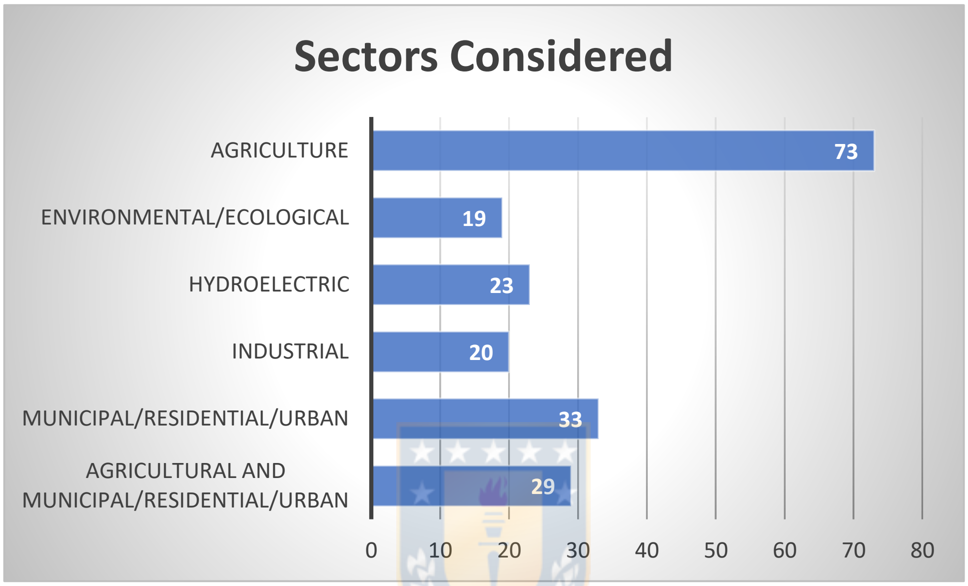
Study	Sectors considered
Ward and Lynch (1996)	Hydroelectric/Instream and downstream recreation
Chatterjee, Howitt, and Sexton (1998)	Agriculture/Hydroelectric
Rosegrant et al. (2000)	Agriculture/Hydroelectric/Industrial/Municipal
Ximing Cai, McKinney, and Lasdon (2001)	Agriculture
Ximing Cai, McKinney, and Lasdon (2002)	Agriculture/Ecological/Hydroelectric
Ximing Cai, McKinney, and Lasdon (2003)	Agriculture/Ecological/Hydroelectric
Ward and Booker (2003)	Instream/Ecological
Ximing Cai, McKinney, and Rosegrant (2003)	Agriculture/Ecological
Draper, Jenkins, Kirby, Lund, and Howitt (2003)	Agriculture/Urban
Jenkins, Lund, and Howitt (2003)	Industrial/Residential
Barbier (2003)	Agriculture/Fishing/Forestry/Residential
Ximing Cai and Rosegrant (2004)	Agriculture
Jenkins et al. (2004)	Agriculture/Urban
Ringler, von Braun, and Rosegrant (2004)	Agriculture/Ecological/Fishery/ Hydroelectric/Industrial/Municipal
Pulido-Velazquez, Jenkins, and Lund (2004)	Agriculture/Urban
Ximing Cai et al. (2006)	Agriculture
Ward, Booker, and Michelsen (2006)	Agriculture/Industrial/Municipal
Ringler and Cai (2006)	Agriculture/ Ecological/Fishery/ Industrial/Hydroelectric/Municipal

Ringler, Huy, and Msangi (2006)	Agriculture/Residential/Industrial/Hydroelectric
Qureshi, Connor, Kirby, and Mainuddin (2007)	Agriculture
Pulido-Velazquez, Andreu, Sahuquillo, and Pulido-Velazquez (2008)	Agriculture/Industrial/Municipal
Ward and Pulido-Velazquez (2008)	Agriculture/Environmental /Urban
Ahrends, Mast, Rodgers, and Kunstmann (2008)	Agriculture
Connor et al. (2009)	Agriculture
Maneta et al. (2009)	Agriculture
Gürlük and Ward (2009)	Agriculture/Ecological/Urban
Alcoforado de Moraes et al. (2009)	Agriculture/Ecological/Industrial
Karimi and Ardakanian (2010)	Agriculture/Industrial
Tisdell (2010)	Agriculture
M Jeuland (2010)	Agriculture/Hydroelectric
Varela-Ortega et al. (2011)	Agriculture
Quentin and Jiang (2011)	Agriculture
Divakar, Babel, Perret, and Gupta (2011)	Agriculture/Ecological/Hydroelectric/ Industrial/Residential
Teasley and McKinney (2011)	Agriculture/Hydroelectric
Yang, Zhao, and Cai (2011)	Agriculture/Ecological/Hydroelectric
Pande, van den Boom, Savenije, and Gosain (2011)	Agriculture
George et al. (2011a)	Agricultural/Environmental/Hydroelectric Industrial/Urban
George et al. (2011b)	Agricultural/Environmental/Hydroelectric Industrial/Urban
M. d. O. Torres et al. (2012)	Agriculture
Hirt et al. (2012)	Agriculture
R Howitt, Medellín-Azuara, MacEwan, and Lund (2012)	Agriculture
Hurd and Coonrod (2012)	Agriculture/Industrial/Municipal/Urban
Yang, Brown, Yu, and Savitsky (2013)	Agriculture
Mullick, Akter, Babel, and Perret (2013)	Agriculture/Fishery/Navigation
Blanco-Gutiérrez et al. (2013)	Agriculture/Industrial /Municipal
Wu, Jeuland, Sadoff, and Whittington (2013)	Agriculture/Hydroelectric
Marc Jeuland, Harshadeep, Escurra, Blackmore, and Sadoff (2013)	Agriculture/Environmental/Hydroelectric
D'Agostino, Scardigno, Lamaddalena, and El Chami (2014)	Agriculture
Akter, Grafton, and Merritt (2014)	Environmental

Qureshi, Whitten, and Kirby (2014)	Agriculture
Ponce et al. (2014)	Agriculture
Welsch et al. (2014)	Agriculture/Hydroelectric
Bekchanov, Bhaduri, and Ringler (2015)	Agriculture/Industrial/Municipal/Urban
Esteve, Varela-Ortega, Blanco-Gutiérrez, and Downing (2015)	Agriculture
Davijani, Banihabib, Anvar, and Hashemi (2016)	Agriculture/Industrial/Municipal
Fernández, Ponce, Blanco, Rivera, and Vásquez (2016)	Agriculture
Kuhn, Britz, Willy, and van Oel (2016)	Agriculture/Ecological/Municipal
Ponce et al. (2017)	Agriculture
Darani, Kohansal, Ghorbani, and Saboohi (2017)	Agriculture
Warfe, Tisdell, and Research (2017)	Agriculture/Environmental
Dogan et al. (2018)	Agriculture/Urban
Emami and Koch (2018)	Agriculture
Mirchi et al. (2018)	Agriculture/Urban
Patel and Ramachandran (2018)	Agriculture/Industrial/Municipalities
Porse et al. (2018)	Industrial/Residential
da Silva and de Moraes (2018)	Agriculture/Hydroelectric
Carini, Maiolo, Pantusa, Chiaravalloti, and Capano (2018)	Scarcity
Kiptala, Mul, Mohamed, van der Zaag, and Management (2018)	Agriculture/Hydropower
Rougé et al. (2018)	Environmental/Urban
Lionboui et al. (2018)	Agriculture/Industrial/Urban
Alamanos et al. (2019)	Agriculture
Martinsen, Liu, Mo, and Bauer-Gottwein (2019)	Scarcity
Haghighatafshar et al. (2019)	Scarcity and Flooding costs
Kahsay et al. (2019)	Agriculture/Hydropower
Ward, Mayer, Garnica, Townsend, and Gutzler (2019)	Agriculture/Urban
Amjath-Babu et al. (2019)	Agriculture/Flood damage/Hydropower
Crespo, Albiac, Kahil, Esteban, and Baccour (2019)	Agriculture/Environmental/Urban
Pakhtigian, Jeuland, Dhaubanjar, Pandey, and Economics (2019)	Agriculture/Hydropower
Mattiuzi, Marques, and Medellín-Azuara (2019)	Agriculture
Dogan, Buck, Medellin-Azuara, Lund, and Management (2019)	Agriculture/Urban
Nover et al. (2019)	Scarcity

M. Torres, Howitt, and Rodrigues (2019)	Agriculture
Liu, Guo, Liu, Zou, and Hong (2019)	Agriculture/Industrial/Urban
Momblanch et al. (2019)	Agriculture/Environmental/Hydroelectric/Urban

Graphic 1: Quantity of Studies per Economic Sector



As it is shown in the Table 1 and Graphic 1, it is clear that the emphasis of HEMs is on Agriculture, while multi-sectorial analysis with sectors with free consumption decisions is not broadly addressed. For instance: 82.02% of the analyzed studies considered Agriculture, 21.34% Environmental/Ecological, 25.84% Hydroelectric, 20% Industrial, and 37.07% Municipal, Residential, or the Urban sector. 32.58% of the studies considered a multi-sectorial analysis with a link between agricultural and residential water consume, while none of the 37.07% studies with residential water consume, nor the 32.58% multi-sectorial agriculture-residential approaches let the residential sector freely decide the amount of water consumed depending on their valuation.

Agricultural HEMs often estimate the water demand as a derivate function from the agricultural benefit, in which water is taken as an input of the production process. The residential demand is modeled as water requirement per households. Rosegrant et al. (2000) models the relation between agricultural, hydroelectric, and municipal/industrial water demands adding the agricultural benefit of water use, the benefit of the households-commercial-industrial use (as a consumer surplus formula), and the electric generation benefit. Jenkins et al. (2003) on the other hand use an economic and industrial loss function in which it calculates the difference between the consumers welfare in the future against the welfare that they would have if they had total availability of water. Pulido-Velazquez et al. (2008) and Ward and Pulido-Velazquez (2008) use a similar loss function but considering the agricultural and municipal/industrial sectors, and agriculture, urban and environmental sectors respectively.

As said in the last HEMs systematic review (Bekchanov et al., 2017) there is a gap in literature respecting to the effects of climate change on water allocation which changes the economic welfare specifically on multi-sectorial distributional impacts. There is a need to assess the effects of various water sector policies to know in more detail the effects of climate change and provide cost-efficient policies that can mitigate the economic effect of it. This is why this investigations address the agricultural-residential water relation, with a HEM perspective.

3. METHODOLOGY

The starting point of this study is the HEM of the Vergara river basin: The Vergara Hydro-economic Model (VHM). The VHM is a mathematical programming model designed to analyze water problems considering the agricultural sector (Ponce et al. (2017)). In this study we modified the original VHM extending the analysis to the residential sector. The VHM has two components: physical and socioeconomic.

3.1 Physical component: The SWAT model

The Soil and Water Assessment Tool (SWAT, Arnold, Srinivasan, Muttiah, and Williams (1998)) was developed by the Agricultural Department of the United States of America in the 1990s. It is a conceptual physical model based on hydrology and water quality, which was developed to predict the impact of different soil management practices in the generation of water, sediments and production of chemical agriculture substances. Its use was potentiated by the possibility of analysis big and complex basins with different types of soil, use of land, and management conditions along different periods of time. The model can be classified as semi-spatial distributed because it uses a mixed based vector in a raster approach (in contrast to totally distributed raster models). For this study, the SWAT model provides the expected changes in water availability due to climate change at the basin level.

3.2 Socioeconomic component

3.2.1 Residential water demand

We rely on previous results to address the residential water demand (Vásquez Lavín, Hernandez, Ponce, & Orrego, 2017). As it was mentioned, most of the studies that consider agricultural and residential sectors fix the residential water use to a certain quantity depending on per capita values and projections of population. This study models residential water consumption using a water demand function, which allocate water depending on the value that households place on water consumption. We do this through the minimization of the difference between the consumer surplus associated to the optimum water consumption, against the consumer surplus associated with the amount of water that households would consume if there was total availability of it.

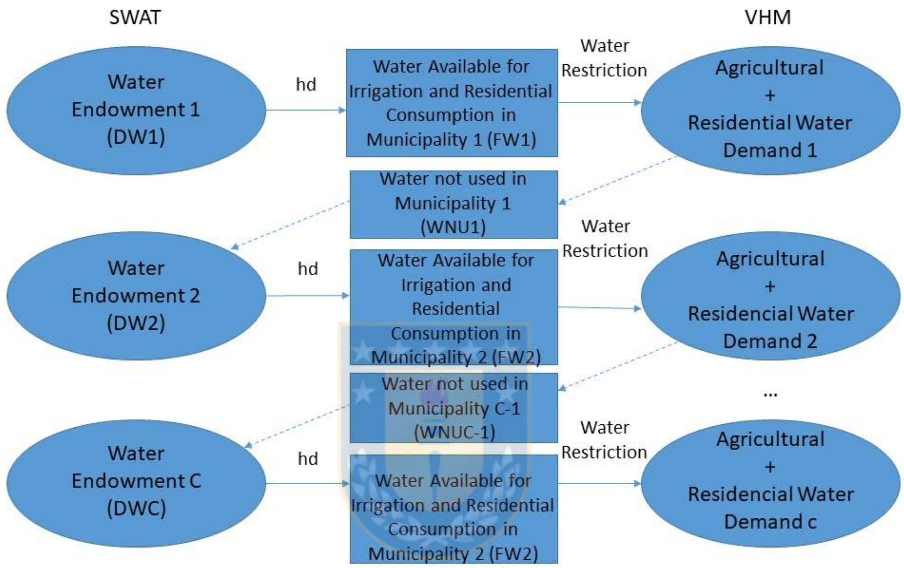
3.2.2 Agricultural water demand

The agriculture water demand is obtained as a derived demand using the Agricultural Supply Model. The Agricultural Supply Model is a mathematical programming model designed to analyze the agricultural sector with a high geographic disaggregation. It includes the more relevant agricultural activities within the area and differentiates between water provision systems (dry and irrigation), among other characteristics (Ponce et al., 2014). The Agricultural Supply Model includes the behavior of agricultural producers (supply). It is characterized by detailed information at a producer level in order to represent a system of outputs and inputs (which rely on the benefit maximization assumptions). The data is differentiated for activity and geographic area, including: planted area, yield, variable costs and labor demand, which is used to compute the total costs, gross margins, and net incomes. The previous information is complemented with supply elasticities per activity. The base model is optimized with a series of endowment restrictions, such as: total land, irrigation land, and water availability.

3.3 Reference Framework of the Integrated Model

The VHM model is a spatially differentiated model in which each commune is the basic unit of analysis and its objective it is to maximize the total surplus (TS) of the basin while minimizing the households' surplus loss (CSD) and maximizing the farmers' surplus (FS) subject to geographic, endowment, and institutional constraints. Within this integrated framework, both water users are linked through the hydrologic system (rivers and channels), thus any decision on water consumption from one agent, will have consequences in others within the basin (Figure 1).

Figure 1: Conceptual Scheme



Previous to the utilization of this model it is necessary to calibrate the agricultural supply function (first step) to replicate the baseline scenario. In this investigation we calibrate the costs, giving a non-linear cost function. To calibrate this function, we use the Positive Mathematical Programming technique, which enables us to replicate the baseline scenario considering both the residential and the agricultural sector.

In the second step, having already calibrated the model, a water supply shock is introduced to the SWAT model using the climate change scenario RCP 8.5, this implies a reduction (average) of -34% in water available for irrigation, adding an increase of temperatures and households according to official projections (INE 2018).

The third VHM step compares the water supply and demand of each user in each commune. In the case that the water supply does not fill the demand of the commune the model redistributes the water between users, activities and communes, distributing the water to the sector which gives it the biggest economic value. It is then when the economic impacts of the climate change are computed as the difference between the TS with and without the climate change. The fourth and final step analyzes policies using cost-efficiency approaches.

3.4 Model Structure

As it has been established before, the objective of the integrated model is to maximize the TS (equation (I)):

$$Max: TS = CSD + FS \quad \text{(I)}$$

If we disaggregate this Consumer Surplus Difference (CSD), it represents the difference between the actual CS and the CS that a total consumption of water would provide. CSD is the sum of all the communal CSD, CSD_c. The residential water demand specification (Vásquez Lavín et al., 2017) is a Discrete Continuous Choice Model. The continuous module is given by equation (II), while the consumer surplus is given by equation (III).

$$Ln\left(W_c^d\right) = \delta Z_c + \vartheta ln(P_c^W) + \gamma Ln(\tilde{y}_c) + \eta + \varepsilon \quad \text{(II)}$$

In (II), W_c^r is the residential water quantity demanded by commune *c*; Z_c is the matrix that contains the households and weather variables which are expected to change the demand in commune *c*; P_c^W is the marginal water price faced by the residential consumer in commune *c*; $\tilde{y}_c$ is the virtual monthly income adjusted by the Nordin difference (Nordin, 1976); η is specified to capture the not observed heterogeneity preferences, ε captures the optimization error derived from the optimum and the observed water consume; and δ, β, γ are parameters that have to be estimated.

Using the parameters estimated in (II), it is possible to compute the CS (Vásquez, Cerda, & Orrego, 2007) represented by (III):

$$CS_c = \frac{P_c^w * W_c^r}{\vartheta + 1} \qquad \text{(III)}$$

In (III) CS_c represents the communal CS. P_c^w represents the fixed marginal water price in commune *c*; W_c^r is the residential water quantity demanded in the commune *c*. The climate change impact on the households welfare (CSD) would be the difference between the CS that they would have with their real water availability against the CS with total water availability (equation IV). We quantify the loss with a lineal approach.

$$CSD = \sum_c (CS_c - (VP_c - P_c^W) * \frac{(W_c^r - W_{cc}^r)}{2}) \qquad \text{(IV)}$$

In equation (IV) CDS represents the Consumer Surplus Difference between real and total consumer surplus, VP_c is the virtual price that the households would have to face with the new changes in the demand curve with free price movement, while W_{cc}^r is the amount of water that households would consume if there was total availability of water. In the baseline $CDS = \sum_C CS_c$, because the amount of money that households should pay is the same as the amount that they are being charged.

On the other hand, the agricultural sector faces a benefit maximization problem, given by equation (V):

$$FS = \sum_{c,a,s} \left((y_{c,a,s} * p_a - AC_{c,a,s}) X_{c,a,s} \right) \qquad \text{(V)}$$

In (V), $y_{c,a,s}$ is the yield in commune *c*, for the activity *a* using the system *s*: irrigation or dry. p_a represents the market price of the activity *a*, while $AC_{c,a,s}$ represents the mean costs of activity *a*, in commune *c*, using the system *s*.

Given the previous formulae, the economic problem would be resumed as the following equations:

$$Max: TS = CSD + FS \quad \text{(I)}$$

$$CS_c = \frac{P_c^W * W_c^r}{\vartheta + 1} \quad \text{(III)}$$

$$CDS = \sum_c (CS_c - (VP_c - P_c^W) * \frac{(W_c^r - W_{cc}^r)}{2}) \quad \text{(IV)}$$

$$FS = \sum_{c,a,s} \left((y_{c,a,s} * p_a - AC_{c,a,s}) X_{c,a,s} \right) \quad \text{(V)}$$

$$AC_{c,a,s} = \alpha_{c,a,s} * (X_{c,a,s})^{\beta_{c,a,s}} \quad \text{(VI)}$$

$$\sum_a \sum_s r_{i,r,a,s} * X_{r,a,s} \leq b_{i,r} \quad \text{(VII)}$$

$$W_c^r + \sum_a IRRDEM_{c,a} \leq W_c^s \quad \text{(VIII)}$$

The economic logic is the following: the agents of the basin (agricultural and residential users) seek to maximize their surplus given by TS (equation I). For residential users the difference between their surplus is given by equation (IV), and the agricultural benefit is defined by equation (V), where farmers use water as an input in their production. The cost function (equation (VI)) that is used in the farmers benefit is calibrated by Positive Mathematical Programming to estimate the value of parameters Alpha and Beta (Blanco, Cortignani, and Severini (2008), Richard Howitt, Medellin-Azuara, and MacEwan (2009). This calibration process replicates the baseline scenarios' per commune, activity, and system (all of this considering the resources restrictions of equation (VII)). Equation (VIII) shows the water restriction of the scenarios, where the sum between the residential and farmers' water use (the sum of crop water irrigation requirements times area planted per commune and activity) needs to be less than the available water per commune. Crop water requirements are defined by given projections, having a with and without climate change water requirement scenarios. After calibrating the cost function to replicate the baseline scenario we proceed to calculate with the SWAT model the new water availability in the climate change scenario, and that quantity is applied to water supply, W_c^s, from equation (VIII), therefore the water consumption from one or both sectors will be forced to decrease. The effect of this water shock on the supply produces a competition between sectors where the one with the biggest valuation uses more water. This water re-allocation ends when both valuations are equal (while land restrictions in equation (VII) and water restrictions (equation (VIII)) are satisfied).

In this way, the results from the new optimum will deliver the new CSD and agriculture benefit, therefore the difference between the baseline scenario TS and post-shock TS will be the economic loss provoked by the climate change.

Within this framework it is possible to analyze the economic consequences of public policies. For example, an improvement of distribution efficiency which mitigate the economic effects of climate change, therefore measures and policies can be evaluated to observe the most cost-efficient action plan.

4. CASE STUDY

The Vergara river basin is used as the territorial unit of analysis. The basin is located 600 km south of Santiago, the Chilean capital. In administrative terms, the Vergara river basin is located in two regions: Biobío and Araucanía region. It is the biggest sub-basin of the Bio Bío basin, one of the most important basins in the country. The Vergara river basin has an extension of 4.260 km2. It includes ten municipalities with a population of nearly 200.000 inhabitants and a great percent of rural population. Small agricultural owners, forestry companies, and fruit exporters are common in the basin economy (Stehr et al. 2008).

The hydrologic cycle of the Vergara river basin is completely dependent of the precipitation patterns and it has a great stationery variability (its maximum flow is in July). Hence any decrease of the precipitation will greatly reduce water availability in the basin. 45% of the basin land use capacity is seriously limited to crop activities, and in those areas, most of the land is destined to forestry. This is mostly so because of land characteristics as slope, soil degradation, and land quality. The actual use of land is dominated by forestry (64%), with a little proportion of agricultural activities (crops and fruits). Even though agriculture is not a representative activity of land use, this activity is the most relevant, with more than 14.000 small farmers under some type of government subsidy program (INDAP, 2014).

Three types of user groups characterize the water demand of the basin: residential, industrial and agricultural. The basin has 59.000 residential water users (households) distributed in ten municipalities. The industrial water demand is dominated by the paper industry, which uses more than 90% of the water utilized by industries. Other water users are the newspaper and leather industry (Navarro, 2006). Considering the agricultural sector, the most water-intensive activities are crops (corn, wheat, beet) and fruits, with more than 38.000 ha under irrigation (INE, 2007).

The main data for the agricultural sector comes from the Chilean Agricultural Census (2007), which was the last detailed farm-level data compilation from the country. This type of Census is taken every ten years, but because of technical and monetary reasons the government postponed the Census from 2017 to 2020. Considering this problem (data that could be different from the one that we are analyzing because of temporal changes) we updated the information with national non-farm level studies. This gives us a regional perspective about how the production of some crops changed, having a better view of crop distribution. We used information from ODEPA to update costs and prices, while the area of each crop planted was updated using regional data from the INE, all to 2018. Residential water demand parameters were taken from a study that has not been published yet using the benefit transfer of unit value method. We acknowledge that these are assumptions that need to be taken into consideration in next studies, and we hope that more data will be available in the near future.

Regarding the residential module, we use results by Rivera Bocanegra (2016), which estimate the residential water demand function with a discrete continuous choice model for Concepción, Chile. That let us consider different block rate prices, which consider the increase price given its consume quantity. We use the estimated parameters while changing the explicative values, with a unit value benefit transfer approach. Concepción and the communes that we analyze are different in their urban population but considering average inhabitants per household and temperature there are no great changes. We can see a minor difference between their monthly income, but considering other choices that we can take to address this agricultural-residential problem we think it is the most realistic approximation.

5. RESULTS

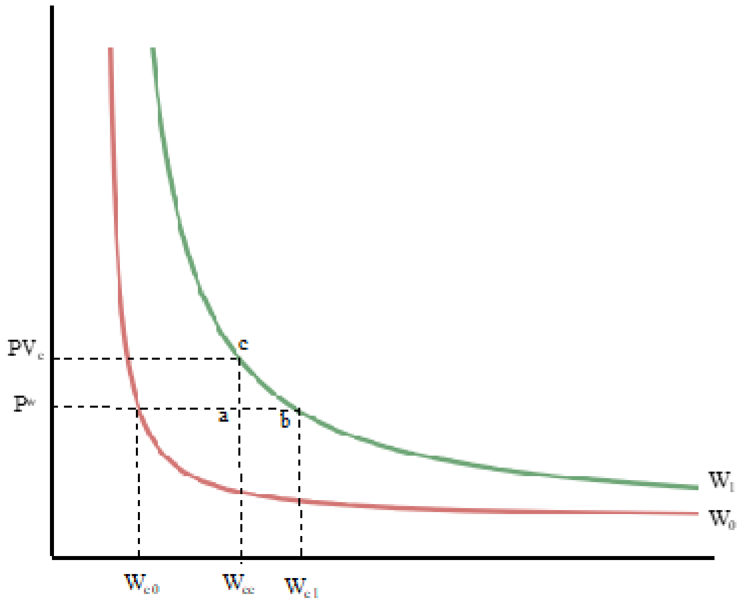
5.1 Scenarios

As we detailed before, after calibrating the agricultural cost function with the PMP process, we simulate three main scenarios, two with and one without government intervention. The calibration presents results which are almost exactly as the ones presented by the updated surveys (less than 1% difference). This calibrated scenario will be addressed as the Baseline Scenario. After this, the first climate change scenario (from now on Climate Change Scenario) presents a change in urban residential consumption (given by rises in temperatures and in the number of households per communes), which implies a redistribution of water between sectors (a move to the residential sector) rising the total surplus. This would happen in a scenario with total availability, but faced with a water supply shock agents have to compete against each other to maximize their own benefit. In this case both agents decrease their water consumption which means that their surplus diminishes from the climate change optimum with total water consumption. The first policy scenario (PS1 from now on) considers an upraise of conveyance distribution of the agricultural sector (10%), which improves the real amount of water that the river delivers to farmers. This improves the farmers surplus and, continuing the ladder, the total surplus. The second and last policy scenario (PS2) considers an improvement in residential water leaks (-15% leaks) which has the same effect as PS1 but via households.

5.2 Water Results

Figure 2 shows how households' water consumption changes between the Baseline Scenario (red curve) and the Climate Change Scenario (green curve), with its real water consumption in a lower amount than the optimum at its price.

Figure 2: Residential Water Demands With and Without Climate Change



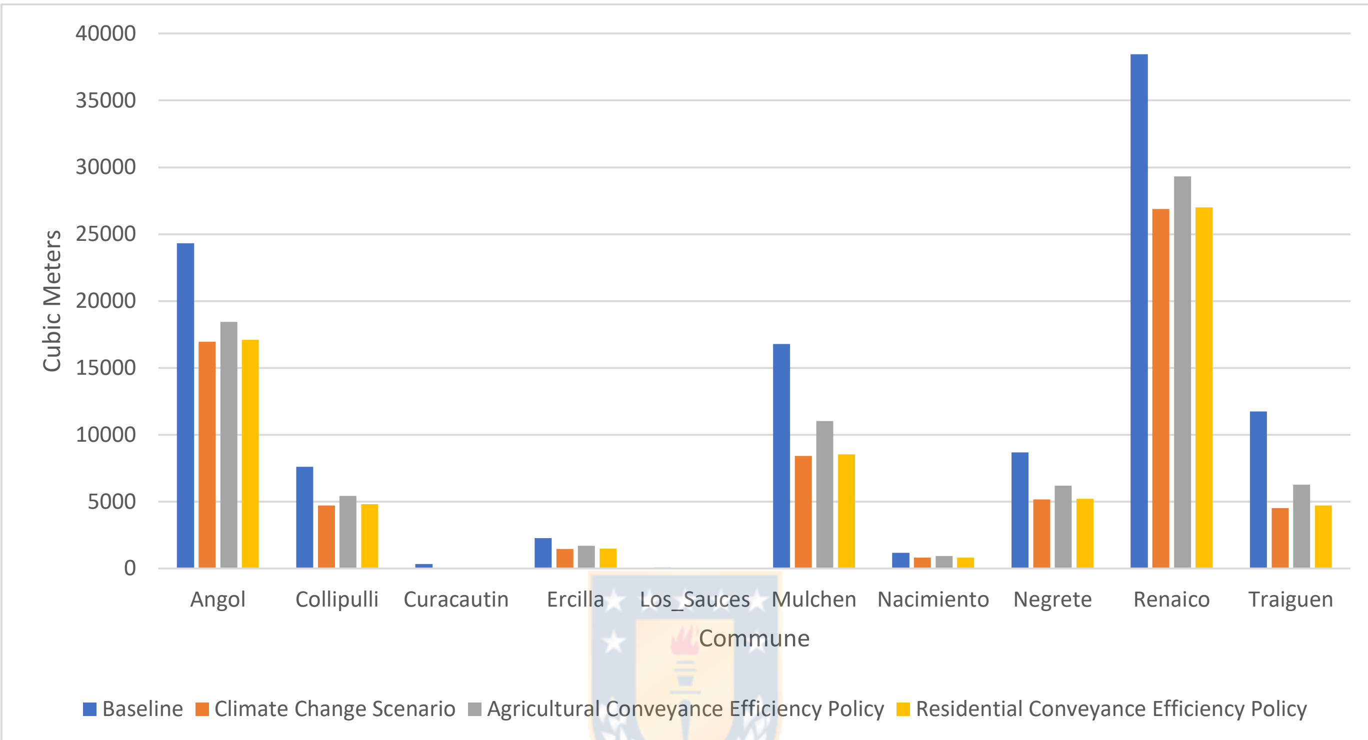
In PS1 water moves to agriculture because it is more efficient to use it in that sector (nevertheless it is a negligible amount). PS2 makes residential consume more efficient, with less water leaks in the water distribution to the residential sector. Residential water consumption is presented in Table 2.

Table 2: Household Water Consumption (m3/month)

Comuna	Baseline	Climate Change Scenario	Agricultural Conveyance Efficiency Policy	Residential Conveyance Efficiency Policy
Angol	13.328	13.585	13.600	13.603
Collipulli	12.664	12.849	12.908	12.878
Curacautin	12.683	11.211	11.164	11.735
Ercilla	12.773	12.891	12.930	12.919
Los_Sauces	12.889	13.137	13.152	13.155
Mulchen	13.129	13.429	13.444	13.442
Nacimiento	12.910	13.183	13.197	13.195
Negrete	13.003	13.308	13.322	13.321
Renaico	13.063	13.352	13.366	13.365
Traiguen	12.921	13.170	13.185	13.188
Total	**129.363**	**130.115**	**130.267**	**130.801**

Regarding agricultural water consumption, its value changes are shown in Graphic 2.

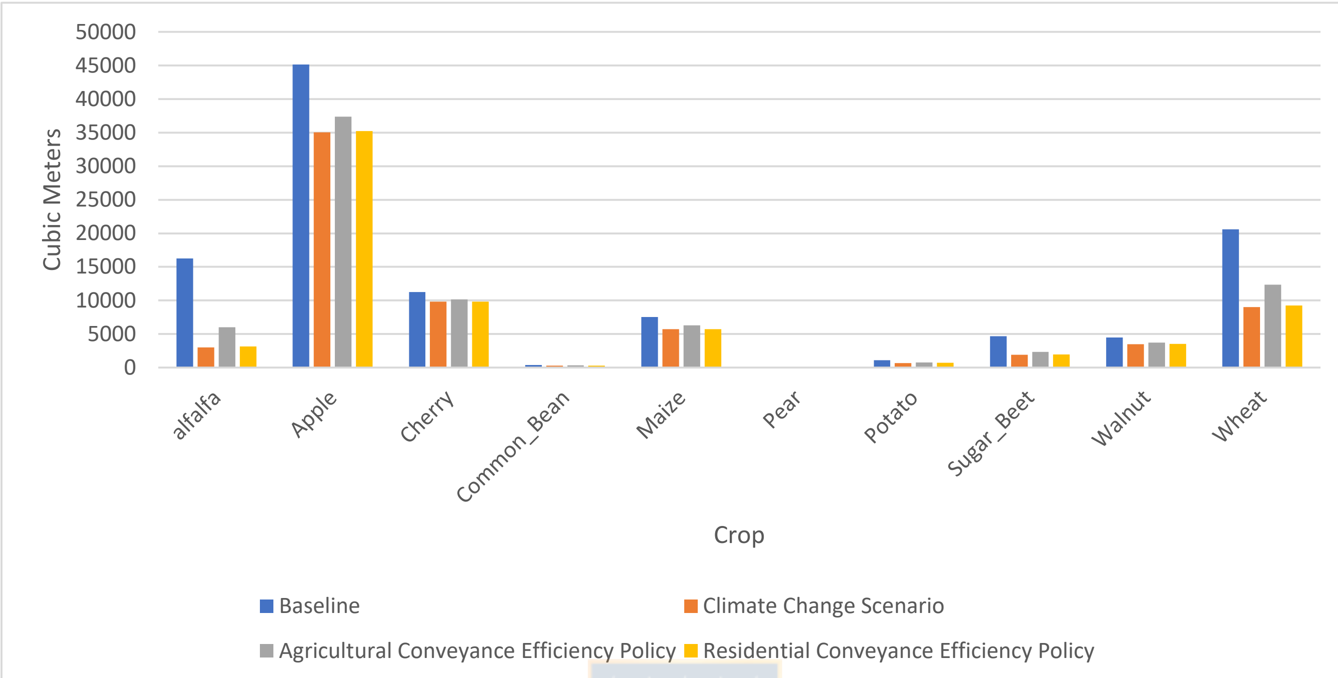
Graphic 2: Agricultural Water Consumption Per Commune



In these scenarios agricultural water demand decreases in a great percent of its Baseline use because of Climate Change and Household increases. Nevertheless, PS1 greatly increases its water consumption because of the rise of agricultural conveyance efficiency, which due to crop decision changes maximizes the economic benefit of farms.

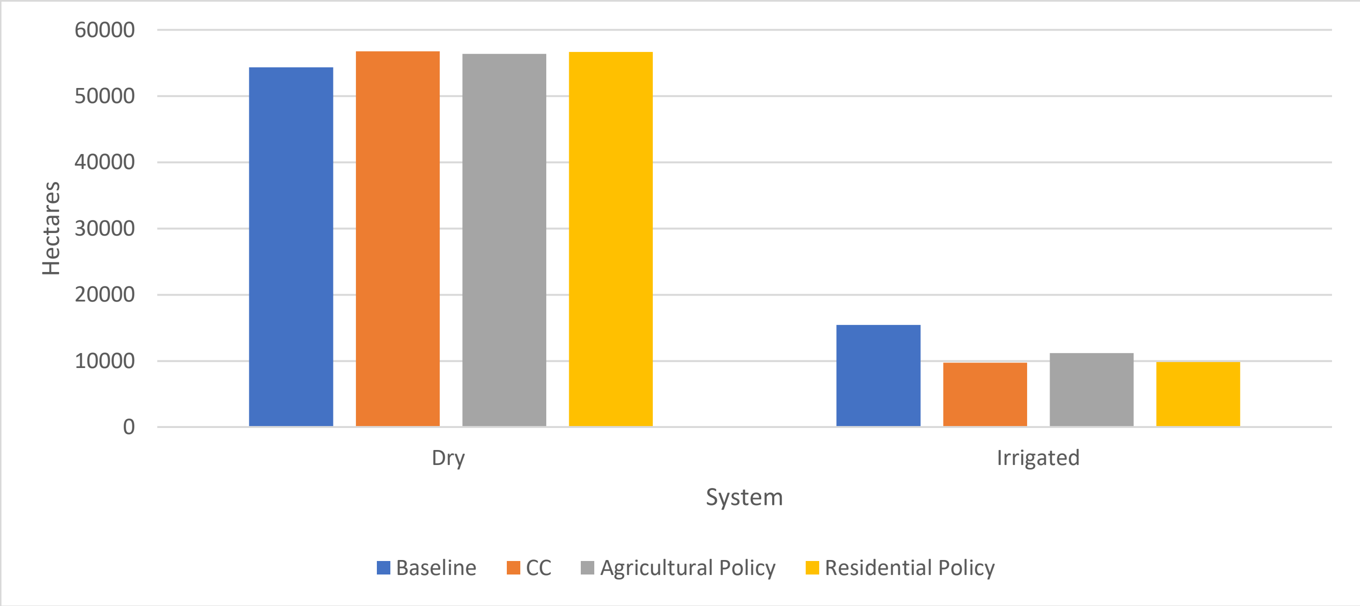
Related to this, changes in crop water consumption varies as shown in Graphic 3.

Graphic 3: Water Consume Per Crop



More notoriously, crop areas change from irrigated to dry planting patterns, which shows an important adaptation between scenarios, as it is seen in Graphic 4. Irrigation land decreases while farms change their crop pattern to dry crops (which need less water).

Graphic 4: Area Planted Per System



5.3 Economic Results

Total Surpluses per scenario are presented in Table 3.

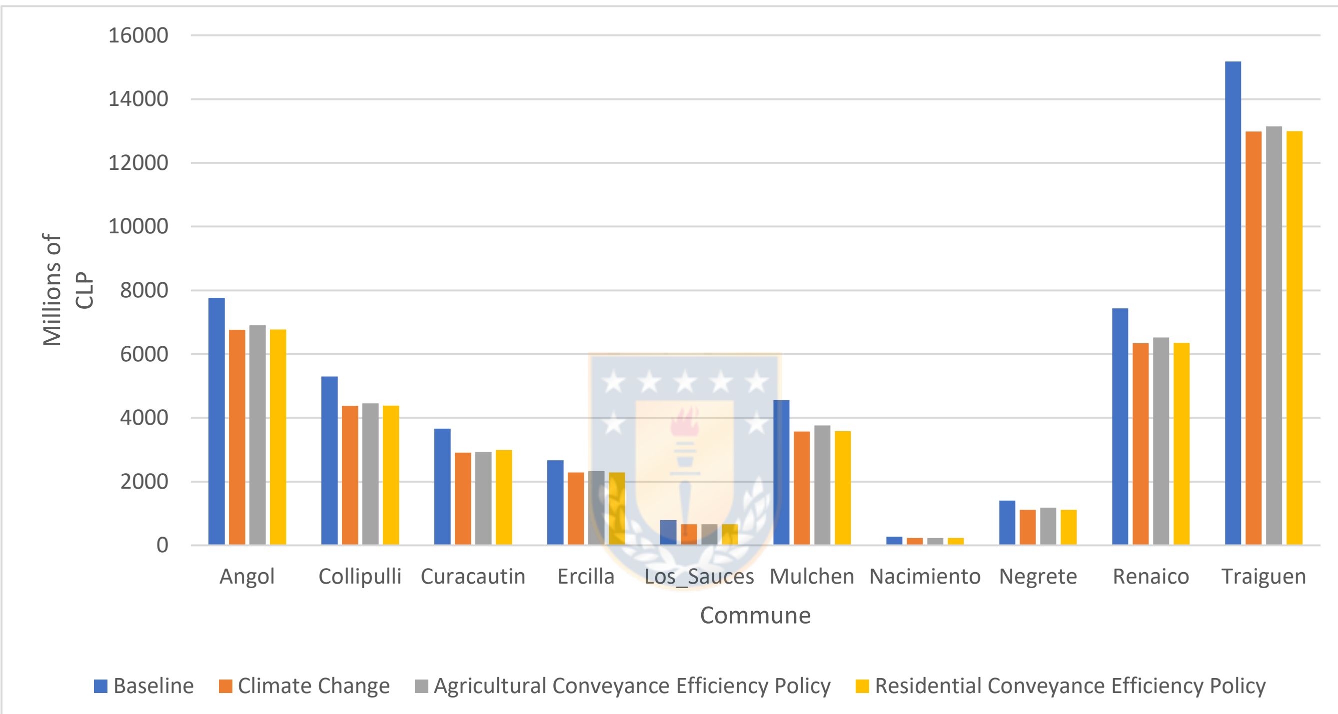
Table 3: Total Surplus Per Scenario (CLP)

Baseline	Climate Change	Agricultural Conveyance Efficiency Policy	Residential Conveyance Efficiency Policy
56,711MM	50,065MM	50,943MM	50,289MM

As seen in Table 3 climate change provokes a loss of CLP 6,646MM, which is almost a 12% decrease from the Baseline Scenario. If we try to mitigate this economic effect with PS1 the basin surplus rises in CLP 878MM (a 1.7% rise), while with PS2 the total surplus rises in CLP 125MM (0.4% rise). We can choose the most cost-effective measure if we know the cost of each one, but this matter falls outside this papers goal.

As we specify in the model, we can disaggregate the economic effect over agricultural and residential sectors. The agricultural sector has big differences within communes, Traiguen being the one with the highest income, while Nacimiento with the lowest. This is presented in Graphic 5.

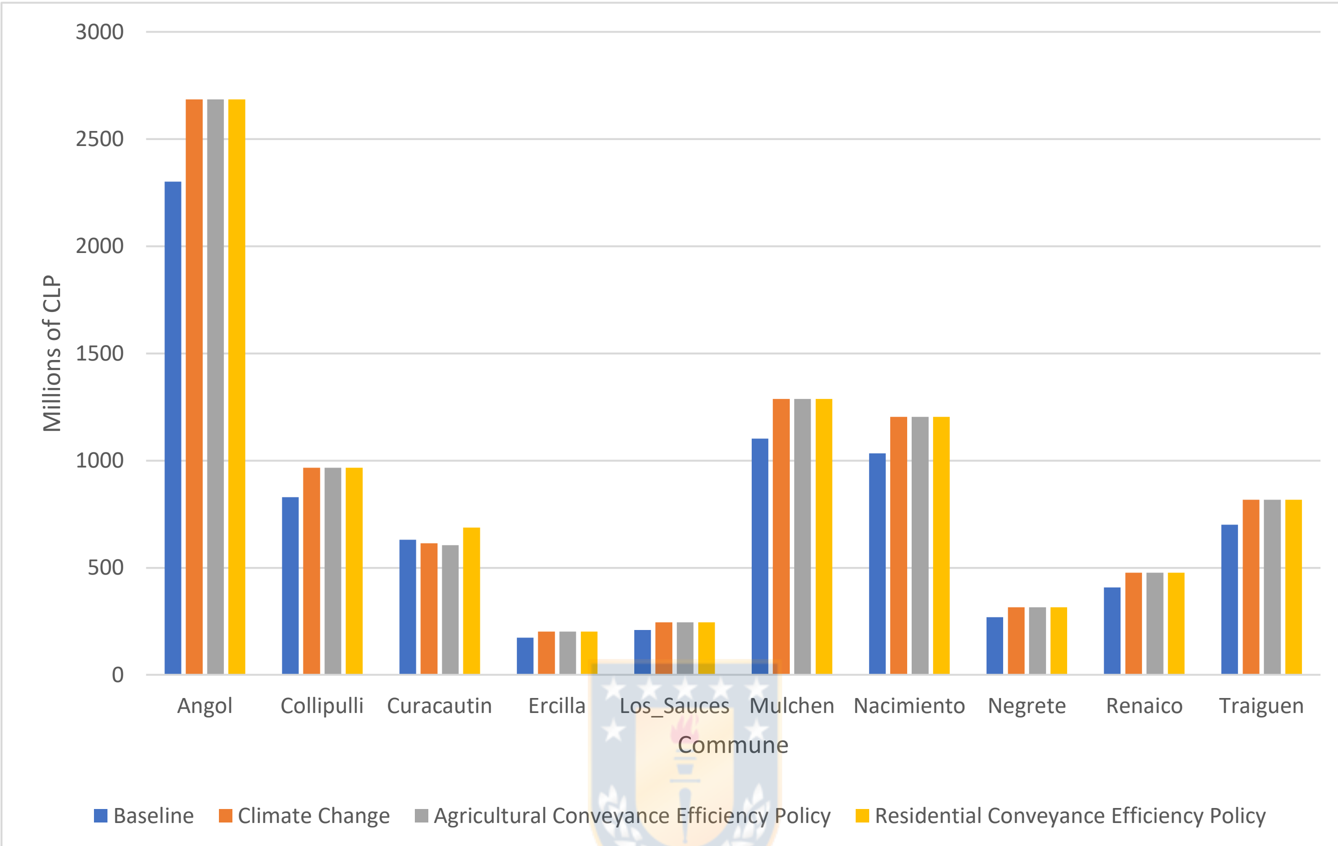
Graphic 5: Agricultural Income per Commune



In every commune changes go in the same direction. With the Climate Change Scenario they all lose a considerable percent of their surplus, on one hand because of the increase of residential water demand, and on the other hand, as a result of the decrease of the total water endowment. It is also seen that PS1 rises their farm surplus in a bigger amount than PS2, but this does not mean that we should choose PS1 over PS2, because we need to also consider their application costs.

If we analyze the residential sector (their consumer's surplus) we have the results presented in Graphic 6.

Graphic 6: Consumer Surplus Per Commune



As it is seen, rises in temperature and amount of households increase the consumer surplus per commune. In Graphic 6 the first change is clear, but in many communes there is no visible change between the Climate Change Scenario, PS1, and PS2. This can be interpreted as if only farms adapt to Climate Change policies. But this is not true, as shown in Table 4.

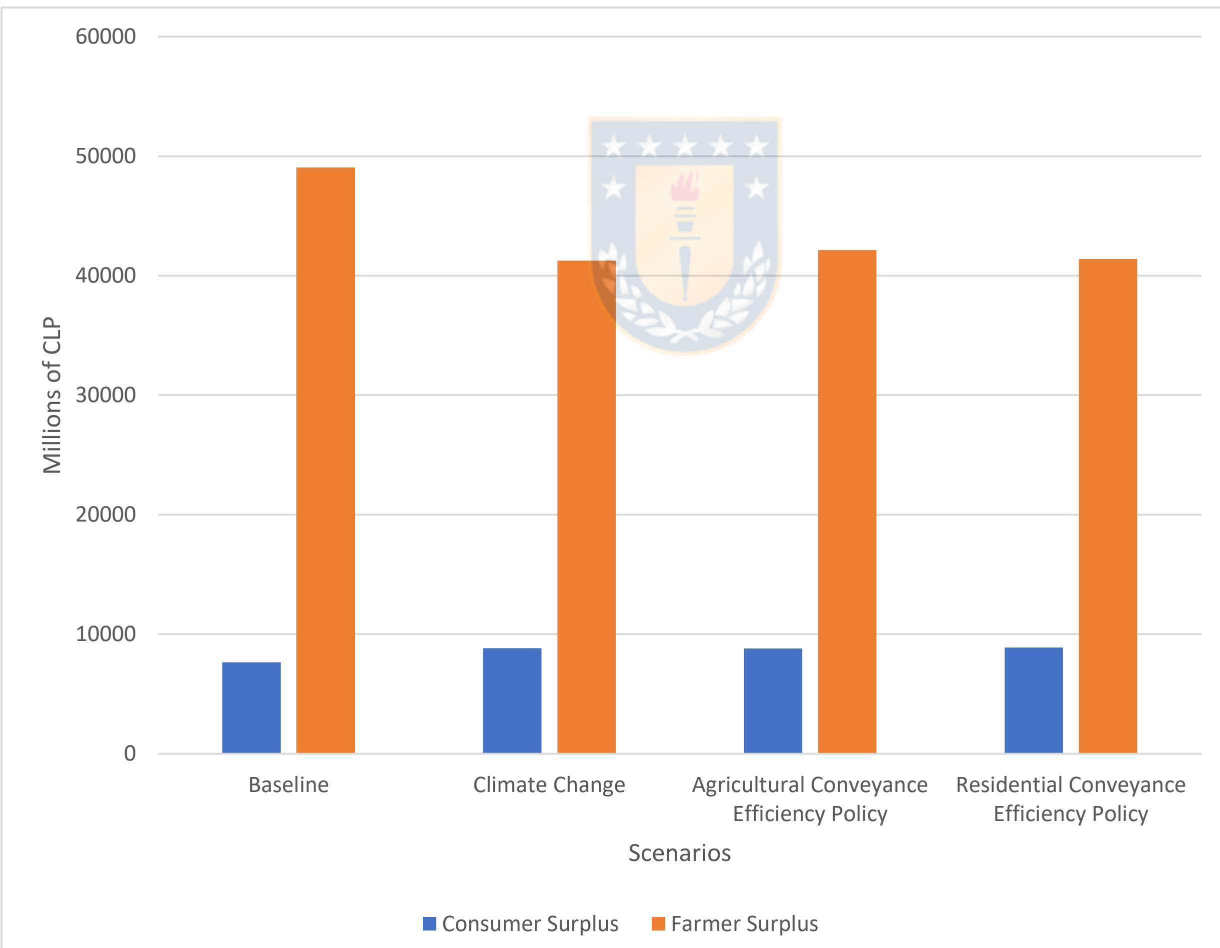
Table 4: Residential Water Consumption Per Scenario (CLP)

Baseline	Climate Change	Agricultural Conveyance Efficiency Policy	Residential Conveyance Efficiency Policy
7,661MM	8,816MM	8,808MM	8,889MM

Table 4 shows how households have a low level adaptation pattern if they are faced against shortages which led farmers to adapt decreasing their consumption in almost all the shortage amount.

For a final analysis we can compare the CS and the FS numerically (Graphic 7). As it is seen, although the amounts of water consumed between agents cannot be compared (the agricultural sector consumes almost the total of water available) surpluses can. It is shown that almost all the adaptation is taken by the agricultural sector.

Graphic 7: Consumer and Farmers' Surplus



This has great consequences in public policies, because now we know (not assume) that changes provoked by Climate Change and households rises will mostly make farms adapt to these new scenarios, being the most damaged by it. We will discuss this in the next Chapter.

6. CONCLUSIONS

After an extensive literature review we denoted that there is a gap regarding inter-sectorial HEMs, more specifically in the agricultural-residential analysis, which in most models only treated the residential sector as a fixed water consumption agent. Nevertheless, the shocks that climate change has in temperatures and water supply, among others, will make this “fixed” sector compete against other water consumers. Policy makers will have a complex task to mitigate the economic effects of these changes.

Southern Chile has a large percent of households which depend on agriculture, so changes in agricultural productivity, precipitations and temperatures will diminish the welfare of a great number of them. Policy makers face even more relevant tasks in the water-distribution process.

The VHM addressed these changes and provided an economic quantitative measure of them. Given the new climate change scenarios we can support the conclusions given by Ponce et al. (2017) who stated that the Vergara river basin economy is vulnerable to climate change (with great reallocations in communes regarding crops). We state and prove that the agricultural sector is the one who will have to adapt improving their water conveyance efficiency, among other tools. Agricultural agents will have to adapt changing their crop patterns to less water-intensive activities, which also are less profitable, as is seen in studies such as in Fernández et al. (2019) and Iglesias and Garrote (2015).

Households will have little adaptation change of their consumption to less water, even more, compared to the baseline scenario they will consume more because of the changing weather and demographic variables. As their willingness to pay (shadow price) is very high they do not change their consumption after the water shortage, which also shows the low adaptability level of its sector. This low adaptability can be interpreted in the way, that giving the amount of water that people want is not only a good faith deal but also an economic efficient distribution, which maximizes the total surplus of the basin, or any size-level area if we compare it to the agricultural sector. We cannot be certain of this if we include other sectors such as beverages or meat, for example.

If we compare the Climate Change scenario against the policy scenarios we can see that policy scenarios improve the total economic surplus, nevertheless it is seen that improvements in agricultural conveyance rises the agricultural profit, while residential conveyance policies rise the households' surplus. Considering these, is that policy-makers need to decide if they prefer PS1 which is the most effective in terms of improving TS and FS, or if they want to mostly rise households' surplus with PS2. The problem now on is not only to improve the basin surplus but to decide which sector will have the highest rise.

Given this research, we can now keep on looking to address new sectors, such as the hydroelectric or industrial, among others. We already know that households will hardly adapt to climate change, but the interactions such as agricultural-industrial-residential, agricultural-hydroelectric-industrial-residential could show a trade-off between sectors that could rise more and better answers to policy makers. Another interesting matter is the analysis of other policies such as price regulations or a mix between the measures considered in this paper.

All these mentioned before, open up more possibilities of studies and new ways to improve our knowledge in HEM's. How people adapt to new circumstances is a subject that we will need to study more and more every time to help policy-makers do their work in the most efficient way. This is our grain of sand, or drop of water in this case.

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