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Nexus Thinking at River Basin Scale: Food, Water and Welfare

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Abstract: Water resources face an unparalleled confluence of pressures, with agriculture and urban growth as the most relevant human-related stressors. In this context, methodologies using a Nexus framework seem to be suitable to address these challenges. However, the urban sector has been commonly ignored in the Nexus literature. We propose a Nexus framework approach, considering the economic dimensions of the interdependencies and interconnections among agriculture (food production) and the urban sector as water users within a common basin. Then, we assess the responses of both sectors to climatic and demographic stressors. In this setting, the urban sector is represented through an economic water demand at the household level, from which economic welfare is derived. Our results show that the Nexus components here considered (food, water, and welfare) will be negatively affected under the simulated scenarios. However, when these components are decomposed to their particular elements, we found that the less water-intensive sector—the urban sector—will be better off since food production will leave significant amounts of water available. Moreover, when addressing uncertainty related to climate-induced shocks, we could identify the basin resilience threshold. Our approach shows the compatibilities and divergences between food production and the urban sector under the Nexus framework.

Keywords: nexus approach; welfare; hydro-economic model; climate change; trade-off effects

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1. Introduction

The environment and the economy are closely interconnected, with the environment playing a twofold role as input supplier and pollutant reservoir, contributing, in the end, to the direct and indirect enhancement of human welfare [1]. Within this environmental role, natural resource availability is limited. Thus, resource allocation across different economic sectors generates trade-off effects, which will likely increase due to the expected future climatic and demographic conditions [2,3].

These interlinkages and trade-off effects are evident when considering the water resources used by two particular sectors: the urban and agricultural sectors. Currently, water resources face an unparalleled confluence of pressures from both humans and climate conditions [4], with agriculture and urban growth as the most relevant human-related stressor [5]. On the one hand, climate conditions are likely to affect urban households' behavior by increasing their water demands [6,7]. In contrast, agriculture is likely to be affected mainly due to water availability changes [8,9]. Moreover, the urban water sector could be even more affected due to demographic stressors, such as population growth [10]. In this context, methodologies using a Nexus framework seem suitable for addressing the water sector's challenges.

The Nexus framework recognizes the interdependencies and interconnections among multiple sectors sharing natural resources and different management schemes [11,12]. Notwithstanding, a water sector commonly ignored in the Nexus literature is the urban water sector and its interaction with other Nexus components (i.e., agriculture) [13]. Using an innovative Nexus framework, we consider the economic dimensions of the interdependencies and interconnections among different sectors, including the urban water sector.

From the beginning, the Nexus approach was conceived from a security perspective related to water, energy, and food supply [14]. However, this approach has evolved in different dimensions, such as the Nexus term's conceptualization, the type of approach, the considerations of the components in its structure, or the geographical scale, among other improvements. Agriculture as the primary water user has historically been the sector that has received more attention under the Nexus perspective by scholars and practitioners [15]. However, this trend has changed in the last years, as recent reviews have proposed a conceptual knowledgebase framework to incorporate or consider other sectors (i.e., climate, health, or ecosystems) [13]. Despite the latest research efforts, the urban water sector has been ignored without considering how human water consumption affects human well-being and how it interacts with the Nexus approach's other components.

In this study, we contribute to the Nexus literature in two ways: (1) we extend the Nexus framework's components by including urban water use, and (2) we add new evidence to the economic dimensions of the interactions and trade-offs among the Nexus components. In particular, we analyze the economic dimension of the Nexus in terms of food, water, and the welfare associated with urban households' water consumption (FWW hereafter). The latter is included through an economic water demand function at the household level. Our analysis relies on a spatially explicit integrated Hydro Economic Model (HEM) at the river basin scale. We use the Vergara River Basin in Chile as a case study. The proposed approach allows us to identify and assess the trade-offs across water users triggered by future scenarios—This paper addresses changes in resource availability associated with climate change and changes in demographic trends.

The literature on water resources concurs on using the river basin scale to analyze water resources issues [16–18], where each water user's spatial location within the river basin is relevant for water allocation. Thus, HEMs arise as an appropriate tool to quantify river basin scale interactions as these models combine hydrologic and socioeconomic information, providing a systemic view to assist policymakers for water resource management. HEMs aim at maximizing the whole basin's value, income, production, or surplus, subject to different constraints related to institutional, hydrological, and agronomic features [18,19]. Mainstream literature on HEMs provides a detailed representation of both the basin's hydrologic features and the agricultural sector [16,18]. Some studies also include industry, the environment, and the urban sector [16,18,20]. However, despite their appropriateness, the use of HEMs for Nexus analysis is still scarce [21]. For instance, Vinca et al. used a HEM to quantify the synergies and trade-offs within the Indus basin's water, land, energy, and climate systems [22]. Using a HEM for the Brahmaputra River Basin in South Asia, Yang et al. shed light on the conditions under which different development trajectories conflict and where they align [23]. Al-Riffai et al. used a suite of three models that work together to capture the biophysical, energy, and economic impacts of climate change and policy intervention scenarios facing the Eastern Nile Basin [24]. While recently, Do et al. developed and applied a HEM for the Lancang-Mekong River basin. This cross-sectoral and transboundary analysis considered sectors as fishery, hydropower, and agriculture [25]. Although these studies have offered valuable understanding about Nexus interactions at the basin level, helping to identify trade-offs and synergies between sectors, none of them have considered a sector as crucial as the urban water sector.

Literature Review on Nexus Concepts, Components, and Methods

Recent literature reviews of the Nexus Approach [13,14,26] have addressed the evolution of different dimensions. Some of the topics analyzed are the Nexus term's conceptualization, the considerations of the components in its structure, the geographical scale used, and its method. This section will discuss those topics, highlighting the knowledge gaps that frame our proposed approach (FWW).

The concept Nexus, in the beginning, focused on clarifying the physical interlinkages between physical resource systems [27]. However, with time, its conceptualization has become increasingly complex [26], incorporating different environmental, economic, political, and social dimensions [28,29]. There is also a call for using the Nexus framework for addressing new challenges, such as climate change and demographic growth [30]. In this sense, the Nexus concept presents high disparity among the mainstream literature, depending on the studies' objectives [14,26,31]. Some authors have indicated no fixed concept for Nexus [32], while others emphasized that it is dangerous to define a rigid concept [13]. In this sense, the FWW Nexus takes advantage of this flexibility to address economic trade-offs, which will ultimately affect water users' welfare.

Because of this flexibility, the number of elements in the Nexus structure has evolved, finding diverse structures to represent different relationships among two, three, four, or more sectors. Although the original format of the Nexus concept (water-energy-food) continues to be the most used composition, there is increased interest in incorporating new elements to achieve what Cairns and Krzywoszynskab have defined as "integrative imaginary" [33]. The list of elements used within the Nexus framework and its combinations is long and varied [14]. Thus, to characterize this diversity, we defined three groups, which are based on the concepts used in previous Nexus studies [13,26]: (1) the dual-sector approach (DSA), which represents the interaction of two sectors; (2) the three-pronged approach (TPA), which characterizes studies where three sectors are considered within its Nexus structure; and (3) the multi-pronged approach (MPA), which encompasses studies considering more than three-sector interactions.

Our review shows that many studies under the Nexus approach have focused on dual-sector interactions. Some authors indicated that DSAs become extremely popular after the Bonn conference titled "The Water, Energy, and Food Security Nexus– Solutions for the Green Economy" [13]. The most common elements considered within DSA are water-energy or water-food to a lesser extent [14,32]. Some recent examples of the first one can be found in Whang et al., who evaluated the water-related impacts of energy-related decisions [34]. Xie et al. mapped the water-energy dynamic changes in the urbanization process of the past 30 years in the Wuxi city of China [35], while for the water-food Nexus approach, a common focus identified in mainstream literature is reducing water consumption for producing food or increasing water efficiency for producing food [32]. For instance, Jiang et al. assess water resources' sustainability for agriculture considering grain production, trade, and consumption in China [36]. Although the list of examples could be extensive, a theme rarely touched among the literature of Nexus DSAs is considering the economic dimension of these interactions. An example found within the literature is the study of Basheer and Elagib. They studied the relationship between energy generation and water losses by examining the sensitivity of the Water-Energy Nexus to changing dam operation policy, quantifying the benefits (energy production) per unit cost (water losses) [37].

While DSAs have been increasing in the last years, TPAs continue to be the most used approach in the literature, especially in water-energy-food composition [14]. The increase in DSAs has occurred mainly because of the greater simplicity in quantifying and representing the interactions between two elements. However, the approaches that address the three-pronged Nexus's complexity identify cross-sectoral synergies and trade-offs that might otherwise be ignored in DSAs [38]. It is in these kinds of approaches that the flexibility of the concept is evident. Although most of them represent the food-water-energy interaction [25,39,40], there are several examples where common elements, such as Food or

Energy, are replaced with new ones, either to achieve an objective of a particular study or to adapt to a specific context. This is particularly interesting for studies addressing climate change under a Nexus approach. Several studies replace one of the common triad elements (water-food-energy), incorporating climate as a new element to address climate change. There are different examples, such as the water-energy-climate Nexus [41], water-climate-food nexus [42], or studies that maintain the classic triad considering climate as an external factor that affects food-energy-water interactions [43]. Other approaches also incorporate ecosystem [44] or environment [28,45] as key elements due to their responsibility for water, energy, and food production and their association with ecosystem services. TPAs have not always been explicit in incorporating the economic dimension (as in Calderon et al. [46]); the economic dimension has been considered in Nexus methods through integrated models or economic tools [26]. However, modeling methods with new perspectives or flexibility that expands our understanding of the trade-offs and their economic dimensions are still needed.

The Nexus term's conceptual evolution has built a knowledge base that allows researchers to assess more complex problems, such as integrating multiple elements into a single evaluation system [14]. Consequently, MPAs studies have grown considerably. Some recent examples are Sušnik et al., who, through the application of games, explore the Water-Energy-Food-Land-Climate Nexus [47]; Engström et al., who analyzed how local energy and climate actions can affect the use of water and land resources at different scales, under a Water-Energy-Climate-Land Nexus [48]; or Karabulut et al., who proposed a system that describes the interrelations between natural resources used for food, energy, and ecosystems, along the lines of the concept of an ecosystem-water-food-land-energy Nexus [49]. In a recent review, Fernandes et al. [14] highlight that the inclusion of multiple elements within the Nexus, different from the common triad (water-energy-food), mainly results in qualitative studies.

The methods used in Nexus approaches have been discussed and reviewed by several authors [13,26,50–52]. Among these reviews, there is general agreement about scale as a key factor to decide which method should be used [51]. However, the studies (mostly empirical) cover a wide range of scales under the Nexus approach, with studies at the global scale [53], at the national scale [54,55] or at the basin scale [11]. This last one, concurring with the literature on water resources, is particularly suitable for analyzing water resource issues where each water user's spatial location within the river basin is relevant for water allocation. In this context, several conceptual frameworks have been proposed to identify linkages within the food, energy, and water systems [56,57]. However, only a few studies have developed or adopted analytical approaches to quantify the Nexus components' interactions [58].

Based on the previous review, we identify the following topics and knowledge gaps that help us frame the FWW approach: (1) we follow the call for flexibles approaches that can adapt to address particular topics of interest. In our case, the FWW approach allows us to quantify the economic trade-offs within the different Nexus components. (2) Using the TPA, the FWW approach fills a gap identified in the literature, namely the explicit consideration of urban households' water consumption and the magnitude of the economic trade-offs with the other Nexus components. Moreover, the treatment of the climate component used here does not differ from the one used in previous studies, in which the climate component is considered as an external shock/perturbation to the Nexus system. Despite this similarity, we decided to propose an innovative approach that explicitly quantifies the economic trade-offs and interactions among food, water, and household welfare, in the face of a climate-induced shock. (3) We increase the number of studies using the river basin as the analytical scale, increasing the evidence of the Nexus interactions in Latin America.

2. Materials and Methods

HEMs typically use two modeling approaches: (1) A modular approach, which uses a link between both biophysical and socioeconomic modules, where output data from one module provides the necessary input to the other [59]; and (2) the holistic approach, in which all variables are endogenously solved in a system of equations [17].

The HEM used in this study—The Vergara Hydro-Economic model (V-HEM)—Is a mathematical programming (MP) model designed to analyze FWW-related issues, linking users' economic behavior with hydrologic basin characteristics. The model is aggregated at the municipality level, and it is solved through a modular approach, using econometric and optimization methods [60,61]. The strengths of our approach are related to (1) the economic analysis of water users with explicit consideration of their geographical location; (2) the economic modeling of residential water users through an economic water demand, which allows us to consider underneath households' preferences for water consumption; and (3) the explicit consideration of the trade-offs among water users in the face of a climate-induced shock. Despite these features, our approach's main limitation is that water users' behavior is purely driven by economic variables, disregarding other key issues affecting users' behavior such us cultural, social, and institutional settings. The way in which the different Nexus components are modeled is explained below.

The food component is modeled using a non-linear agricultural supply model (ASM), which is a MP model designed to analyze the agricultural sector by allocating land to different agricultural activities. The ASM includes the major agricultural activities—in this particular case, different cultivated crops within the study area and differentiates between water provision systems (rainfed and irrigated), among other features. The water component includes both the households' water demand and the agricultural water demand. Household-level water demand is estimated using a discrete-continuous choice model, which allows us to consider increasing block rate prices [62–64]. On the other hand, agricultural water demand comes from the ASM in the form of derived water demand. Finally, the welfare component includes the households' welfare associated with water consumption (measured as the households' surplus) and the farmers' income associated with food production.

"Nexus thinking" integrates the different components of the FWW Nexus through the basin's hydrologic features. Basin hydrology is modeled using the soil and water assessment tool (SWAT; Arnold et al. [65]). The SWAT model is a conceptual, physically based, hydrological and water quality model. For modeling purposes, the basin is divided into sub-basins; sub-basins are further divided into hydrologic response units (HRU), which are unique combinations of land use, soil type, and slope. The hydrology of the basin is conceptually divided into two phases: (1) the land phase of the hydrologic cycle and (2) the routing phase. Surface water availability at the subbasin outlets is obtained by calculating the water balance at each subbasin HRU and then adding the results to the water coming from the upstream subbasin [66]. In our case, input information consisted of a digital elevation model of the watershed, climate data (temperature and precipitation), land use, and soil type; irrigation was not considered as it is not so relevant in the studied basin. Additionally, crop rotation was not considered [67,68]. Water availability at commune levels was obtained by overlapping subbasin results with the commune spatial distribution.

The V-HEM is a spatially explicit model. Each commune is the basic unit of analysis, whose objective is to maximize the basin's total welfare: households' surplus plus agricultural income. The former is computed by aggregating the households' surplus changes at the commune level using a log-log expression for the residential water demand. In contrast, the latter is computed by aggregating the net agricultural income coming from the ASM at the commune level. The objective function—total welfare—is subject to geographical, resource endowment, and institutional constraints.

2.1. Study Area

Located 600 km south of Santiago, Chile's capital, the Vergara River Basin lies within the Biobío and Araucanía regions. It is the largest subbasin of the Biobío basin, one of the country's most important river basins. The Vergara river basin has an extension of 4260 km^2, including ten municipalities with a total population of almost 200,000 inhabitants, including a large share of the basins' rural population [68]. Agricultural smallholders, forestry companies, and fruit exporters characterize the basin economy. On the other hand, the hydrologic cycle within the Vergara river basin depends entirely on rainfall patterns. It exhibits large seasonal variability, i.e., runoff peaks during July and low flows during the summer. Thus, any decrease in rainfall patterns will lead to a decrease in water availability within the basin [68].

Although agriculture is not the representative land use, it is the most relevant activity in socioeconomic terms, with more than 14,000 smallholders distributed across the basin, with an average farm size of 20 ha [69]. Regarding activities, 52% of farmers allocate some of their lands to cereals (oats, maize, and wheat), legumes, and potatoes [70]. On the other hand, the basin has 59,000 residential water users (households) distributed within ten municipalities. ESSBIO, a private water utility, serves those households.

2.2. Model Specification

Figure 1, Panel A, presents the conceptual model. Panel B shows the basin's map and the communes that compose it, while Panel C shows the Vergara River Basin's water flows through the different communes. Figure 1 (Panel A) shows that the water available in each commune (FW) depends on the water endowment computed through the SWAT model (DW) and a water conveyance efficiency parameter (hd). Under this setting, FW restricts the total amount of water used by both households and farmers. Further, each community could use all the water available or leave some water (WNU) for the downstream community (color dash lines). In this case, the unused water in an upstream community will increase the water endowment downstream. For the calibration process, it is assumed that supply matches the total water demand at the baseline scenario.

As established above, the objective of the V-HEM is to maximize the total surplus, which is composed by farmer's income (*FI*) associated with food production plus households' surplus (*HS*) associated with in-house water consumption (1).

$$Max: \; TS = FI + HS \tag{1}$$

Farmer's income, related to food production, is represented in Equation (2), in which $X_{c,a,s}$ denotes the area devoted to activity a (cultivated crop) in community c using system s (rain-fed or irrigated), $AC_{c,a,s}$ represents the vector of average costs per unit of activity a in community c using system s, pa is the price of activity a, and $y_{c,a,s}$ is the yield per hectare of activity i in community c using system s.

$$FI = \sum_{c}\sum_{a}\sum_{s}(y_{c,a,s} * p_a - AC_{c,a,s}) * X_{c,a,s} \tag{2}$$

Equation (3) is the calibrated cost function $(AC_{c,a,s})$. Within this equation, the parameters $\alpha_{c,a,s}$ and $\beta_{c,a,s}$ were derived from a profit-maximizing equilibrium using Positive Mathematical Programming—PMP– [71–73].

$$AC_{c,a,s} = \alpha_{c,a,s} * (X_{c,a,s})^{\beta_{c,a,s}} \tag{3}$$

The *HS*, related to water consumption, comes from a household-level water demand estimated in a previous study conducted in the same region [74]. The specification for the residential water demand is presented in (4).

$$Ln(W_C) = \delta Z_c + \vartheta Ln(P^w) + \gamma Ln(\widetilde{y}_c) + \eta + \varepsilon \tag{4}$$

where W_c is the monthly household water demand in commune c; Z_c is the matrix of household characteristics and climate variables (i.e., house characteristics, number of inhabitants, and temperature) that are thought to shift the water demand in commune c; P^w is the marginal water price faced by households; $\widetilde{y}_c$ is the virtual income or monthly income adjusted by the Nordin difference [75]; 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 δ, ϑ, γ are the parameters to be estimated.

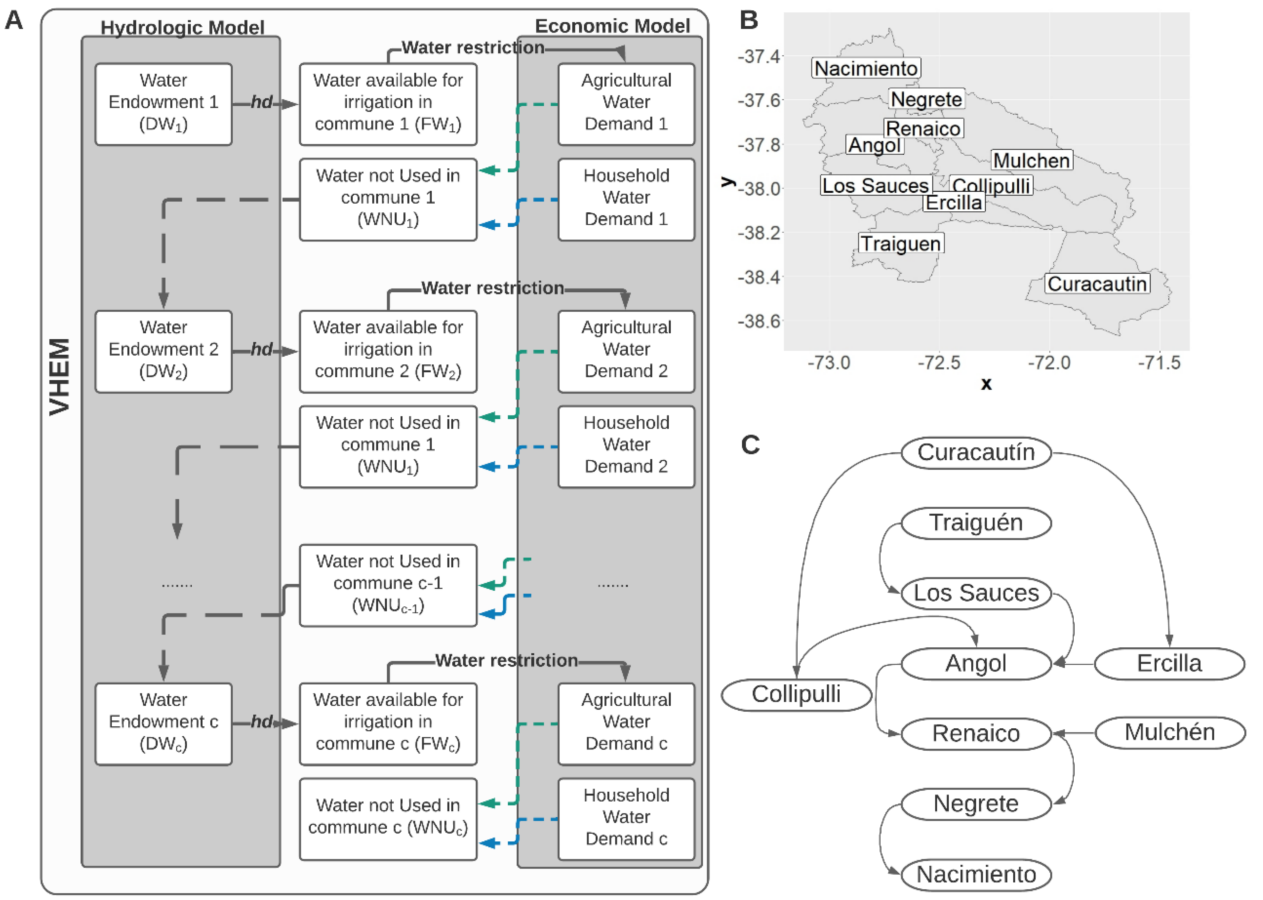

Figure 1. (**A**) Conceptual model; (**B**) basin map; (**C**) water flow through the basin's communes. Green dashed arrows: agricultural water not in use; blue dashed arrows: household water not in use.

Assuming that household water demand will shift rightward when temperature increases [63,76,77], the situation with and without climate change and the *HS* is presented in Figure 2. W0 represents the current household water demand curve, W1 represents the water demand curve under the climate change scenario, while P^w is the water price that is assumed to be fixed due to institutional restrictions. W_{c0} represents the household water consumption in commune c under the baseline scenario, while W_{c1} represents the household water consumption in commune c under the climate change scenario. Notice that W_{c1} assumes that households will get all the water they want under this new scenario. However, the model allows that, due to water competition between households and agriculture, households could leave some water for the agricultural sector. Thus, the household water consumption under the climate change scenario (assuming competition for water) is W_{cc}. As P^w is fixed, a virtual water price (PV_c) is needed to compute the household surplus in commune c.

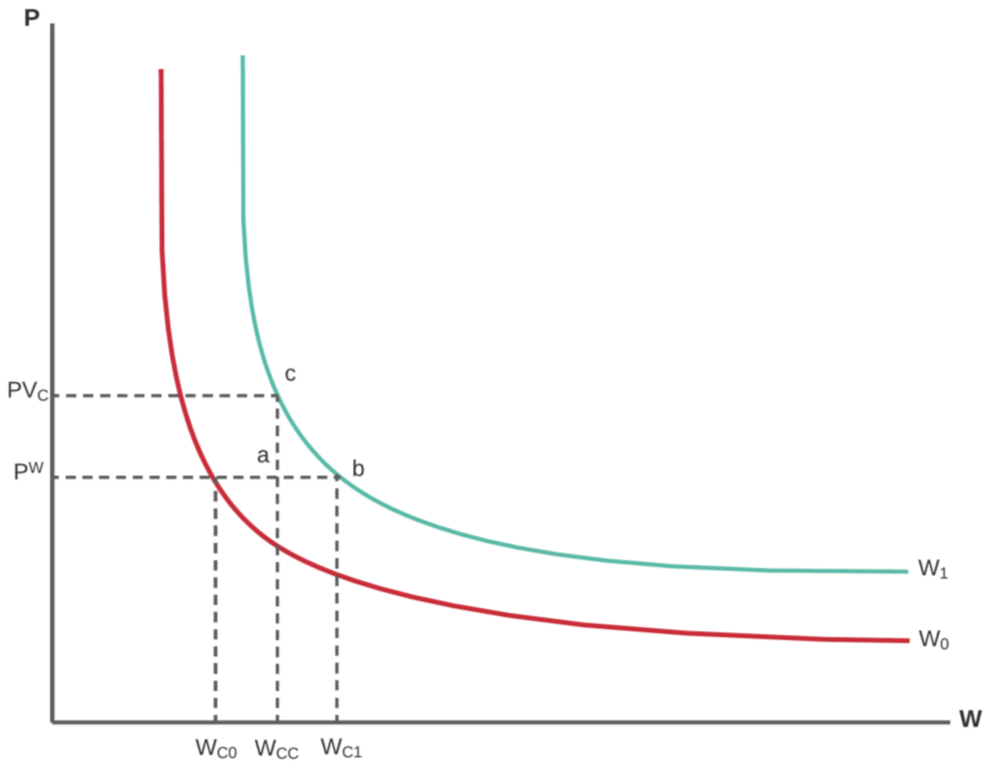

Figure 2. Household water demand and consumer surplus.

The *HS* under the climate change scenario is the difference between the area under the W1 demand curve (and above P^w) and the welfare loss associated with leaving some water for food production (agriculture). For simplicity, we approximate this area to the triangle *abc*. Using the parameters estimated in (4), it is possible to compute *HS* (5).

$$HS = \sum_{c=1}^{C} \frac{P^w \times W_{c1}}{\vartheta_c + 1} - \frac{[(PV_c - P^w)(W_{c1} - W_{cc})]}{2} \tag{5}$$

In (5), the first component $\left(\frac{P^w \times W_{c1}}{\vartheta_c + 1}\right)$ represents the *HS*, assuming that urban households will get all the water they need, while the second component represents the effect of water competition between users $\left(\frac{[(PV_c - P^w)(W_{c1} - W_{cc})]}{2}\right)$.

Finally, the Nexus thinking is represented in Equations (6) to (10). In Equation (6), FW_c represents the water available in community c, which is equal to the total water demand: (1) the crop irrigation requirements of irrigated activity a ($fir_{c,a,irr}$) multiplied by the land allocated to it, plus (2) the yearly household-level water demand (W_c) in commune c, multiplied by the number of households in 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 hd_{uc} of user u (farmers and households) 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, Equations (9) and (10) show resource restrictions associated with total land and irrigated land.

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

$$FW_c \leq (DW_c + WNU_{-c}) \times hd_{uc} \tag{7}$$

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

$$\sum_{a}\sum_{s} X_{c,a,s} \leq tland_c \tag{9}$$

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

2.3. Data and Simulation Scenarios

Fourteen activities represent the agricultural sector, aggregated according to the following categories: annual crops (irrigated and rainfed potatoes and irrigated common beans), cereals (rainfed oat, irrigated maize, and irrigated and rainfed wheat), fruits (cherries, plums, peaches, apples, walnuts, and pears; all irrigated) and other crops (alfalfa and sugar beet, both irrigated).

The core information used in the model (area, production, yield) is dated from 2007 and came from the National Agricultural Census [78], considering disaggregation at the communal level. The information about costs per commune, activities and watering systems (irrigated, rainfed), and labor intensity is the same information used in a previous study developed by the Agrarian Policies and Studies Bureau (ODEPA, its Spanish acronym) [79]. The agricultural information and economic information have been updated to 2018 using information published by ODEPA [80]. Prices were taken from the ODEPA website [81], and the elasticities used for the PMP model's calibration were collected from previous studies [82–84]. We also assume the values of the water conveyance efficiency parameters for agriculture (0.6) and the urban sector (0.65) based on previous studies [85,86].

Climate change impacts on water resources are simulated, shocking the SWAT model's water availability with different climate change scenarios. We develop nine scenarios based on Chile's Third National Communication on Climate Change [87], which provides the expected changes in temperature and precipitation for the periods 2011–2030 and 1991–2010 based on the results of the PRECIS Regional Climate Modeling system. This model operates at a 25 km resolution, considering two representative concentrations pathway (RCP), such as RCP 2.6 and RCP 8.5. Nine scenarios were constructed as combinations of temperature and precipitation change using RCP 2.6 and RCP 8.5 as lower and upper boundaries, respectively, in which temperature changed within the range [+0.5 to +1.0] °C, whereas precipitation changed within the range [−10 to −15]%. Using this information, the hydrologic module estimates an average reduction (50th percentile) of −34% in water available at the basin level (E5). Table 1 presents the changes in each commune's water availability for each of the nine simulated scenarios.

Table 1. Change in water availability by commune (compared with the baseline).

	Water Availability Scenarios								
Commune	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**
Ercilla	−21.4%	−21.5%	−21.8%	−31.2%	−31.98	−31.5%	−40.6%	−40.7%	−40.8%
Mulchén	−24.9%	−25.1%	−25.3%	−36.0%	−30.71	−36.3%	−46.2%	−46.4%	−46.5%
Curacautín	−24.6%	−24.8%	−25.2%	−35.7%	−33.16	−36.3%	−46.2%	−46.4%	−46.6%
Traiguén	−21.8%	−22.0%	−22.2%	−31.8%	−35.51	−32.1%	−41.3%	−41.5%	−41.6%
Collipulli	−23.6%	−24.1%	−24.1%	−34.7%	−32.96	−35.4%	−45.2%	−45.7%	−46.0%
Nacimiento	−23.3%	−23.7%	−23.6%	−34.3%	−35.09	−34.8%	−44.7%	−45.1%	−45.3%
Los Sauces	−24.2%	−24.5%	−24.8%	−35.3%	−31.23	−35.9%	−45.7%	−45.9%	−46.4%
Negrete	−20.8%	−21.1%	−21.3%	−30.4%	−34.62	−30.9%	−39.6%	−39.8%	−40.1%
Renaico	−22.3%	−22.8%	−23.2%	−32.6%	−35.43	−33.4%	−42.5%	−42.8%	−43.2%
Angol	−22.2%	−22.9%	−23.6%	−32.6%	−35.86	−33.7%	−42.8%	−43.4%	−44.0%

The expected changes in water availability represented by each scenario depend on the expected changes in the climatic variables (temperature and precipitation). In this context, the most optimistic scenario (E1) is characterized by +0.5 °C and −10% decrease in precipitations, whereas the most pessimistic scenario (E9) is characterized by +1 °C and −10% decrease in precipitation. On the other hand, we assume that climate change would also affect agricultural productivity, while the increase in temperature will affect households' water consumption. In this sense, we assumed that rainfed productivity would decrease by 10%, while irrigated productivity would decrease by 5%, based on previous studies [88,89]. Meanwhile, urban residential water consumption, determined by rises in temperatures, is expected to increase. All the above variables (changes in water availability, crop yields, and temperature) are jointly considered to simulate scenario 1. Finally, a second scenario is formulated considering the same variables mentioned above, plus the expected changes in the basin's demographic trends. According to official projections [90], the number of households will increase by 13% (on average). Table 2 shows a summary of both scenarios.

Table 2. Simulated scenarios.

Scenarios	Stressors Considered and Impacts Modeled
Scenario 1	**Climatic Stressors** A decrease in water availability A decrease in crop yields Increase in temperature
Scenario 2	**Climatic Stressors** A decrease in water availability A decrease in crop yields Increase in temperature **Demographic stressors** Population growth

3. Results

Our Nexus assessment captures the driving forces behind water allocation across sectors, in which both water users—farmers and urban households—define their water consumption decisions aimed at allocating the resource to its most valuable use in terms of economic value. The results are presented according to the Nexus' component: food, water, and welfare. The food component breakdowns into four elements: tons produced of *cereals* (oat, wheat, and maize), tons produced of *fruits* (apple, cherry, walnut, and pear), tons produced of *annual crops* (potatoes and common bean), and tons produced of *other crops* (sugar been and alfalfa). The water component, as well as the welfare component, is divided into two elements. The water component is divided into *agricultural water use* (thou of m^3) and *household water use* (thou of m^3), whereas the welfare component is divided into *agricultural income* and *household surplus* (both in millions of Chilean pesos, MM$).

One of the advantages of using a bottom-up approach such as the one used in this study is that it allows us to conduct Nexus analysis on two levels: aggregated, in our case at basin level; and disaggregated, in our case at commune level. At the aggregated level, Figure 3 shows the change in %, relative to the baseline, of the Nexus components (food, water, and welfare) and its associated elements under both scenarios. As it is shown, the food component (with all its elements) is the most affected, with *other crops* (alfalfa and sugar beet) showing the largest decrease: −66% (scenario 1) and −67% (scenario (2). This change is triggered by a decrease in land allocation to these crops, from 1990 hectares to 590 hectares (scenario 1) and 568 hectares (scenario 2). The *annual crops* element is also heavily affected under both scenarios, but its change is not that large, unlike the *other crops* element. This can be explained because the *other crops* element is entirely dependent on water availability for irrigation.

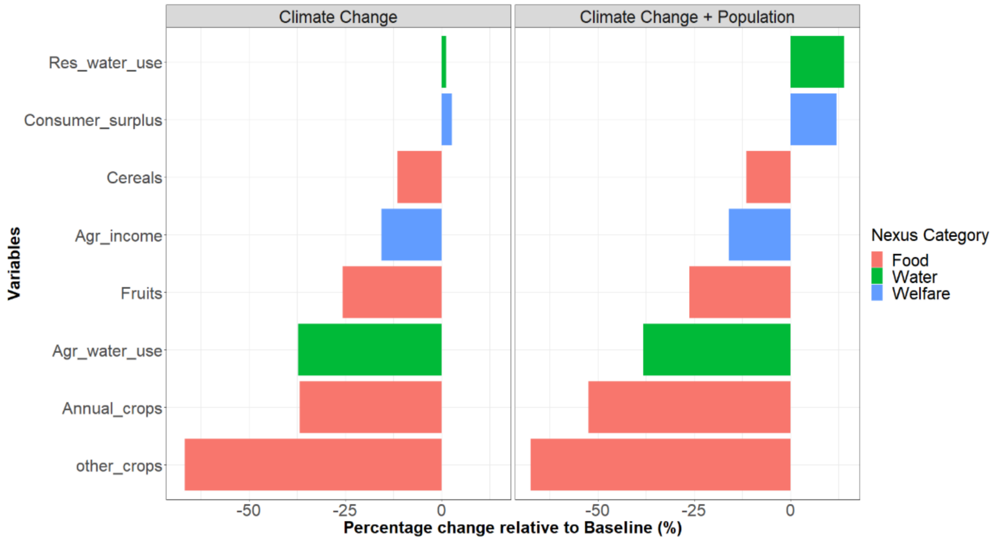

Figure 3. Aggregated results for each scenario.

Among the different Nexus elements, only those related to the household sector show positive changes: *household water use* and *household surplus*. For instance, in scenario 1, the expected changes in climate variables have a marginal effect on a household's water demand, with a slight increase in *household water use* (+1.2%), but this increase in water use drives a change in *households' surplus* (+2.7%, from 7661 MM$ to 7871 MM$). On the contrary, when considering climate variables and demographic trends (scenario 2), the changes are quite relevant, with *household water use* increasing by 14% (from 8159.5 to 9301.7 thou of m^3). In contrast, the change in *household surplus* is 12% (from 7661 MM$ to 8816 MM$).

All the changes described above will impact the welfare component, which changes by −11.7% (from 56,711.3 to 50,065.7 MM$). Thus, at the aggregated level, it seems that the extreme future conditions simulated, with an average decrease in water availability of 34%, will not impose a significant burden on basin well-being. However, these aggregated figures hide significant changes among the different Nexus elements, which could be uncovered through a disaggregated analysis.

Disaggregated analysis is conducted comparing the baseline with scenario 2, as this scenario includes all the changes in future conditions (climate and demographic). Figure 4 shows the change in tons of each element of the food component. The first thing to note is the spatial distribution of each group of crops. For instance, *annual crops* (Panel A) are mainly produced within the southern communes of the basin (Traiguén and Curacautín), and *cereals* are in the upstream communes (Panel B). In contrast, the *fruits* group (Panel C) and *other crops* (Panel D) are mainly produced downstream in communes like Angol and Renaico.

The *annual crops* element, which is one of the most affected by climate change at the basin level, is significantly affected in the south-upstream commune of Curacautín. The production decreases −87%, from 2631 ton to 345 tons. Additionally, important changes are also observed in the other crops element's production (alfalfa and sugar beet). In this case, the most significant decrease is shown in downstream communes such as Renaico (−35%, from 49263 ton to 17318 ton) and Angol (−29%, 22392 ton to 6450 ton). It is important to highlight that although the elements *fruits* and *cereals* also present some degree of change in production, the effects are not as notorious as in the other group of crops (*annuals crops and other crops*).

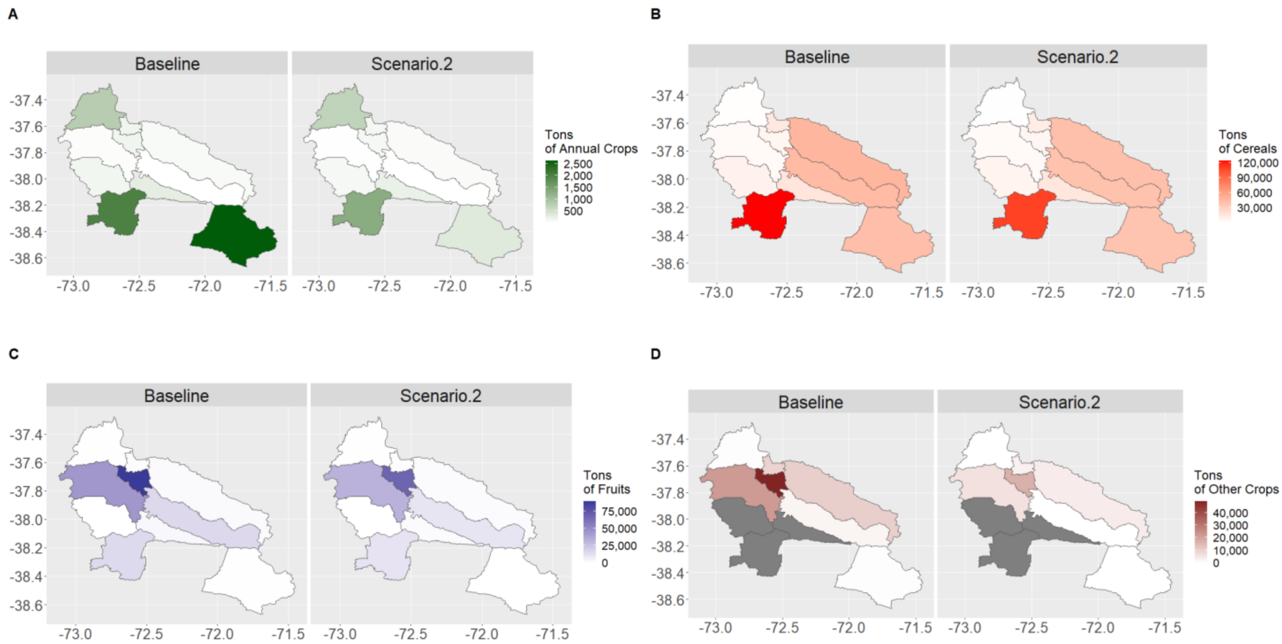

Figure 4. Change in the food components (tons produced) within scenario 2.

As discussed at the basin level, the water component analysis shows uneven changes between its elements (*household water use and agricultural water use*). These changes are linked to the amount of water transferred between communes in the face of future conditions. Panel A of Figure 5 shows that under scenario 2, communes like Mulchen, Traiguén, and Los Sauces present the largest water transfer to downstream communes: 4442, 4408, and 4205 thou m^3, respectively. On the other hand, Negrete and Renaico show the lowest water transfer to downstream communes: 913 and 320 thou m^3 (the other communes used all its available water). For instance, the largest transfer of water is observed from Mulchen to Renaico (4442 thou m^3), which is also the commune that reduces its *agricultural water use* the most. This apparent contradiction is explained because Renaico is the commune that faces one of the largest decreases in water availability due to climate change (−35,4%). Thus, the commune should reduce its *agricultural water use* and adapt to this new scenario despite the water transfer.

An interesting situation is observed in Traiguén, Los Sauces, and Angol. The basin's hydrologic features dictate that Traiguén is linked with Los Sauces and Los Sauces with Angol (see Figure 1, Panel C). In the face of scenario 2, Traiguén transfers 4408 thou of m^3 to Los Sauces, despite the fact that Traiguén is hardly affected regarding changes in water availability (−35.5%). The interesting thing is that Los Sauces is characterized by having nearly 99% of rainfed land. Thus, an important transfer of water occurs from Los Sauces to Angol, the most affected commune regarding water availability changes (−35.8%) and the commune with the basin's largest population. Based on the final water allocation between users—agriculture and households—we could suppose that this water transfer is mainly devoted to covering human consumption. Curacautín, located at the head of the basin, is the only commune that decreases *household water use* and *agricultural water use*. However, the decrease in *household water use* is relatively small (−0.07%).

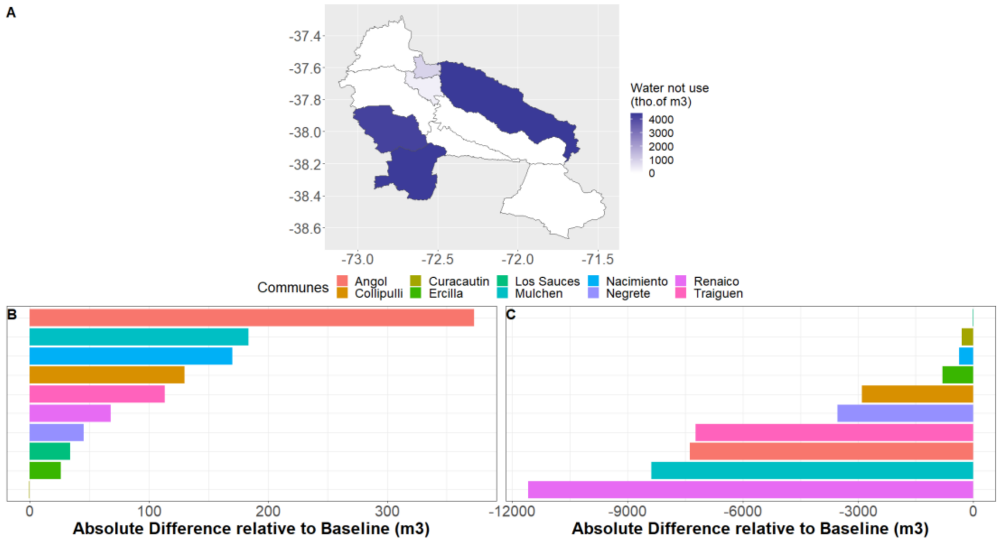

Figure 5. Changes in the water component (m^3). (**A**) Water not used by communes after scenario 2. (**B**) Difference of water used compared to the baseline from the agricultural and residential sectors.

Finally, the welfare the Nexus component is analyzed considering the predicted changes in each commune's total surplus and the elements that composed it, namely *agricultural income* and *household surplus*. Panel A of Figure 6 shows that the predicted changes of scenario 2 will decrease the total welfare in almost all of the basin's communes, except for Nacimiento, which increases the total surplus by 127 MM$. This is mainly explained by the slight decrease in *agricultural income* (nearly 44 MM$) and the large increase in *households' surplus* (171 MM$).

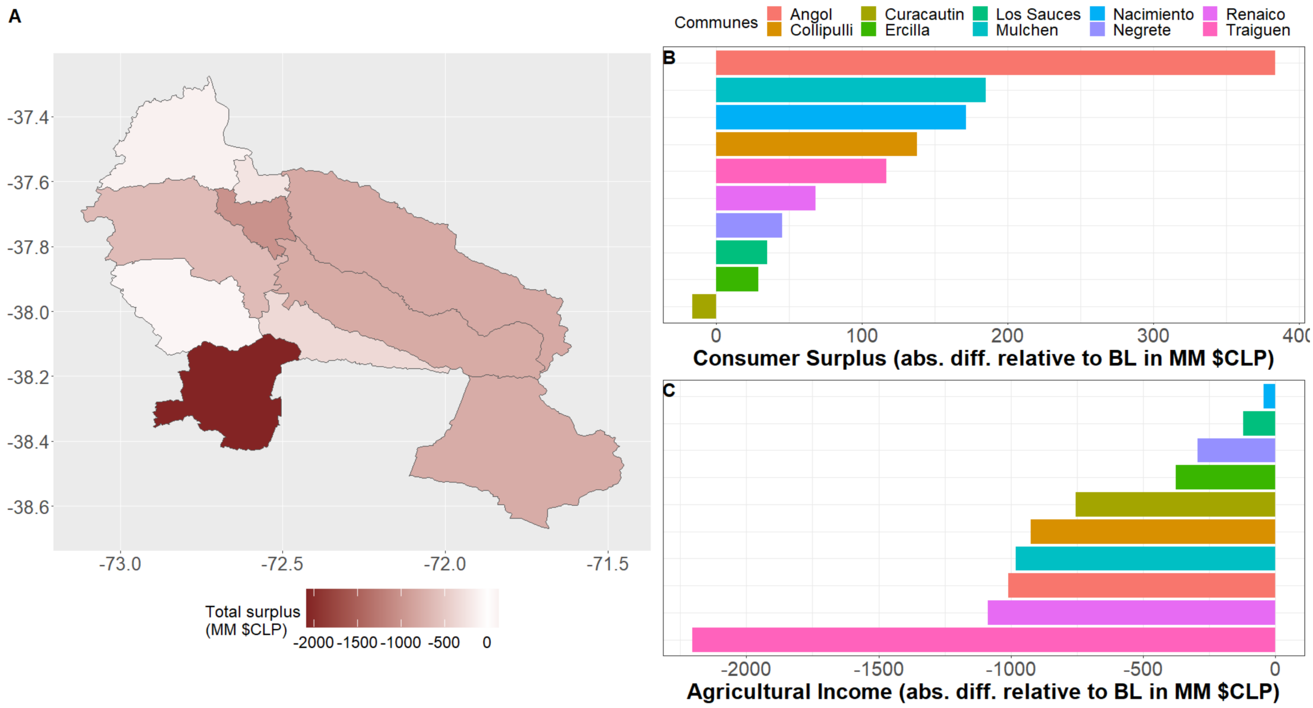

Figure 6. Changes in the welfare component (MM $CLP). (**A**) Total Welfare in scenario 2 by commune. (**B**) Household surplus change within scenario 2 by commune. (**C**) Agricultural income change within scenario 2 by commune. All data in MM$.

On the other hand, as we can observe from Panel B and C of Figure 6, scenario 2 will have impacts in opposite directions when comparing *households' surplus* and *agricultural income* (except for Curacautín, in which both elements have the same negative direction). As both temperature and population increase, households will use more water, driving an increase in the households' welfare for almost all the communes. On the other hand, the new conditions will decrease food production, decreasing farmers' income. All the changes described above will impact the total basin welfare, which decreases by $6645.6 million (−11.7%).

To address the uncertainty related to climate-induced shock, Figure 7 shows the likely changes of agricultural income, consumer surplus, and total surplus for the whole set of climate scenarios used. As expected, the stronger the negative shock, the greater the economic impact. As shown, for decreases in water availability greater than 40% (E7, E8, and E9), the negative economic impact on agriculture, urban households, and the whole basin is extremely high, well below the median. These results suggest that extreme changes could jeopardize the basin's resilience to climate-induced shocks.

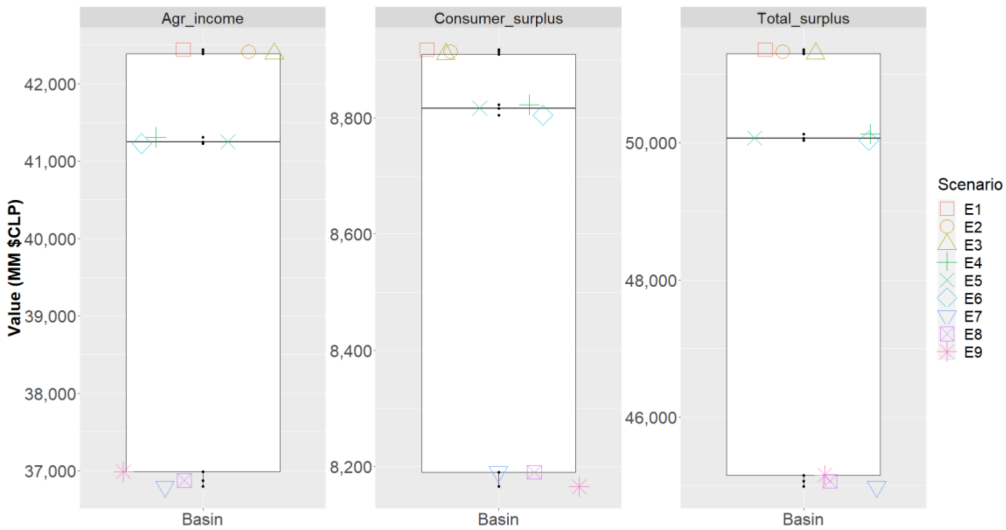

Figure 7. Agricultural income, consumer surplus, total surplus under 9 scenarios of water availability change. All data in MM$.

4. Discussion

From a Nexus perspective, this study highlights how households' water consumption interacts with other components under future climatic and demographic conditions. We identified and quantified the different trade-offs between agriculture and urban households as water users within a common basin. We present results at aggregate and disaggregate levels in the context of climate change and demographic stressors. Although not commonly considered in the mainstream literature, there have recently been calls for its consideration under a water security perspective [13,15].

According to our review, the proposed FWW Nexus approach has the flexibility to address particular topics of interest [13,32], allowing us to quantify the economic trade-offs across the Nexus components. Using this approach, we also fill a gap identified in the literature [13], namely the explicit consideration of urban households' water consumption and the magnitude of the economic trade-offs with other Nexus components.

Our results show that most Nexus components are highly affected under simulated future climatic and demographic conditions. Under both scenarios, the food component is affected by changing the array of cultivated crops at the basin level. There are large reductions in water-intensive activities, especially those within the groups of *annual crops* (irrigated potato or common bean), *other crops* (such as alfalfa and sugar beet), and irrigated cereals (such as irrigated wheat). This is in line with previous studies, which also reported changes in cultivated crops in favor of less water-intensive activities under climate change scenarios [91]. Moreover, this new crop allocation is traduced in a decrease in food production within the basin. From a food security perspective, this could bring high levels of uncertainties in a territory where several agricultural communities are oriented to subsistence agriculture (predominantly indigenous communities) [92]. Our results are in line with previous studies using HEM within the Nexus framework, in which precipitation is key for the basin's future, especially for food production [23]. Moreover, as reported by Do et al., the use of HEM allowed us to identify overlooked trade-offs [24,25], in our case, the role of irrigated agriculture in fostering the urban sector's adaptation to climate-induced shocks.

Regarding the water component, its elements (*agricultural water use* and *household water use*) present opposite responses to both scenarios at the basin level. On the one hand, the changes predicted in the food elements, in which land is allocated to less water-intensive activities, reduce agricultural water use, leaving significant water available for the urban sector. On the other hand, households do not reduce their water use despite the reduction in water availability due to climate change, as water use is positively affected by temperatures [63,76,77]. Nevertheless, even more than climate change, our results show that demographic stressors are likely to impose larger effects on the urban water sector, highlighting the importance of considering multiple stressors on Nexus approaches, especially those with water centrality [7]. An important issue arising from these results is related to the negative impacts that climate change could have on small-scale agriculture and the increase of rural-urban migration. Considering that population has significant effects on the urban water sector, two questions arise for future research: could the increase of rural migration put pressures on water supply systems to meet urban water demand? Could this effect increase competition with water abstraction for irrigation?

Considering aggregated effects over the welfare component, our results also show opposite responses between sectors. The change in the cultivated crop array also translates into an adverse change in agricultural income. On the contrary, our results show that the households' welfare increases under both scenarios. These changes are produced by prioritizing water allocation under the profit-maximizing behavioral assumption when water is scarce. The priority of use is allocated to households, since they show the largest economic value (shadow price). These findings are in line with a recent body of literature that assesses household priority under water-competing settings [5]. However, it is essential to understand that if sectors with larger shadow water prices were considered, these could completely change the results presented here, which, in extreme cases, could even drive water shortages at the household level [93].

Our uncertainty analysis showed that for extreme scenarios of changes in water availability, the expected negative impacts for each water user are high. These results are similar to previous studies, the objectives of which have been to assess climate change impacts under Nexus approaches. As for Berardy and Chester [94], our results show that under certain levels of a decrease in water availability, farmers can cope, in our case, through endogenous adaptation (represented by changes in crop allocation). However, if water scenarios become even more significant, agriculture could present important decreases in their income.

Our findings are based on the economic principles of optimizing water allocation across users. This rational behavior is clearly a limitation of our approach, as water users' behavior is affected by other issues like cultural, social, and institutional context, besides economics factors [77,95]. This limitation is especially relevant in contexts in which institutional settings are not based on free-market principles, which is not the case for Chile [96,97].

5. Conclusions

In this work, we have identified and quantified the effects of climate change and demographic stressors on different components of the FWW Nexus, through a HEM for the Vergara River Basin. Our approach draws on two scenarios that simulate the increasing pressures that water users will face due to population growth and climate stressors on water resources. Particularly, in the context of the Nexus approach presented here, we provide insights into the different trade-offs at the basin level, demonstrating the compatibilities and divergences between different water sectors.

From a policy perspective, our results represent autonomous adaptation that, under climatic and demographic stressors, water users from the Vergara River Basin (the urban households and agricultural sector) would carry out. Moreover, as we assume that water freely flows across the basin, we mimic the conditions of a perfect water market in which water is allocated to its most valuable use. In this sense, a perfect water market enables any adaptation strategy to simulated changes.

These adaptation strategies are dependent on the level of the shock faced, with extreme water scarcity scenarios driving extreme economic impacts. This situation imposes several challenges to water policy. For instance, it is necessary to identify basin resilience thresholds above which stronger and faster policy interventions are needed.

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