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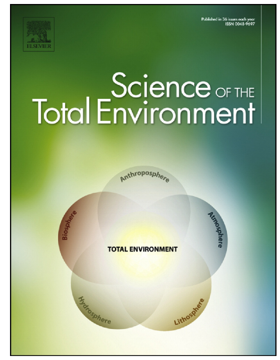

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Understanding agricultural water footprint variability to improve water management in Chile

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ABSTRACT

Understanding water consumption is crucial for sustainable management of water resources. Under climate change scenarios that project highly variable water availability, the need for public policies that assure efficiency and equity in water resources is increasing. This work analyzes the case of the Cachapoal River agricultural basin (34°S 71°W), which presents temperature increases and a precipitation deficit, with a drought period that began more than eleven years ago having significantly decreased water availability. Water consumption in the basin for food production was determined from the agricultural water footprint ($WF_{agricultural}$), using the green (WF_{green}), blue (WF_{blue}) and gray water footprint (WF_{gray}) indicators, which were measured in the upper, middle and lower basin under conditions of climate variability (dry, wet and normal years). The greatest $WF_{agricultural}$ was established in the dry year, with a total of 18,221 m^3t^{-1}, followed by 15,902 m^3t^{-1} in the wet year and 14,091 m^3t^{-1} in the normal year. Likewise, the greatest WF_{blue} and WF_{gray}, of 12,000 m^3 t^{-1} and 4,934 m^3 t^{-1}, respectively, were also observed in the dry year. The greatest WF_{green}, 2,000 m^3t^{-1}, was calculated for a normal year. The 63% of agricultural area of the basin was covered by avocado (*Persea americana*), olive (*Olea europaea*), corn (*Zea mays*) and grape (*Vitis sp*) crops, which presented the greatest $WF_{agricultural}$. This water footprint data provides a quantitative basis for the assessment of water consumption and degradation, considering agricultural production and its multiple variables. The success of the application of these results lies in the use of indicators to understand change processes and complement future water allocation plans with more rational water management models.

Keywords: Water consumption, climate variability, water management, scarcity, basin.

1. Introduction

Climate variability and competing water intake flows or demands make water a scarce, vulnerable resource (Hejazi et al., 2014; Hoekstra et al., 2016; Miglietta et al., 2018). The water footprint (WF) is an indicator of water resources use that allows the volume of water directly or indirectly consumed or polluted for the production of a good or service to be determined (de

Miguel et al., 2015; Pellicer-Martínez and Martínez-Paz, 2018). Thus, it is a useful tool for addressing the imbalance between the supply of and demand for various water flows (Chukalla et al., 2017; Qian et al., 2018).

The water footprint (WF) requires information on water flows, vegetation dynamics and human needs. River runoff and groundwater infiltration are known as the blue water flow. The green water flow is the precipitation that is temporarily stored in the soil and on top of vegetation. The gray water flow is the water necessary to replenish the environmental carrying capacity after a human intervention (Hoekstra, 2014; Liu et al., 2017). Globally, it is estimated that around three fifths of precipitation takes the green path and two fifths the blue (Lovarelli et al., 2016). Consequently, the three components of the WF are: 1) WF_{blue}, which is the volume of blue flow water taken up for industrial, domestic and agricultural irrigation purposes; 2) WF_{green}, which is the consumption of green flow water that sustains the production of crops, pasture land, forestry plantations and ecosystems; and 3) WF_{gray}, which is the volume of water required to assimilate or dilute pollutant or fertilizer inputs (Cazcarro et al., 2015; Hoekstra et al., 2016; Hoekstra, 2017).

The WF_{crop} is defined as the water consumed as a result of evapotranspiration, irrigation requirements and fertilizers applied during the growing period, according to climate and soil characteristics and crop parameters; the sum of the water consumption of each crop ultimately determines the $WF_{agricultural}$ of the basin (Salmoral et al., 2011; Schyns et al., 2015; Chukalla et al., 2018).

Establishing water consumption in a river basin contributes to the sustainable and efficient management of water resources. The unconsumed portion of the extracted water returns to the system and remains available for downstream use; thus, water quality and the destination of the returned water are important (Hoekstra et al., 2012). Nonetheless, there are few studies that address the assessment of the $WF_{agricultural}$ in river basins, particularly in the case of mediterranean regions, where agriculture requires irrigation to compensate for drought periods (Billib et al., 2009; Cortés et al., 2012; Pellicer-Martínez and Martínez-Paz, 2018). In such areas, blue and green water availability is variable, due precisely to rainfall irregularity; thus, agriculture in these areas is the greatest water consumer (Ercin et al., 2013). Switzerland (Hoekstra, 2015) and California (Fulton et al., 2012) are examples.

In the last 25 years of research on water management in agriculture, the greatest efforts have been made mainly in Asia (China, India), North America (United States), Oceania (Australia) and Europe (Germany), while in Latin America the field is still emerging (Velasco-Muñoz et al., 2018).

The economy of Chile, a Latin American country rich in mediterranean landscapes, is based on the use and extraction of natural resources, including water (Donoso, 2006; Cortés et al., 2012). Agriculture accounts for 80% of consumptive extractions of water, allowing the irrigation of over 1.1 million hectares; the irrigated area has increased annually, especially into previously unused areas, an expansion aided by the application of technology (Donoso et al., 2016; DGA, 2016). Global climate change trends will also produce greater vulnerability as increasing water demands become more difficult to meet, with projections for 2040 indicating general water reduction in central Chile (32°S to 33°S), where the largest amount of cropland is concentrated (Iglesias and Garrote, 2015; Pino et al., 2015; Chartzoulakis and Bertaki, 2015). Added to these trends is the drought period that began on 2007, with a precipitation deficit of 30% and temperature increases between 0.5 °C and 1.5 °C above the historical average (Boisier et al., 2016; Valdés-Pineda et al., 2016).

The foregoing suggests the need for public policies that ensure efficiency and equity in water resources (Jaramillo and Destouni, 2015). Water regulation in Chile is a major challenge. It is based on a market model governed by the Water Code of 1981 (DFL 1.122), which entails a combination of a (centralized) distribution system and (freely transferable) water use rights (Hearne and Donoso, 2014; Rivera et al., 2016). In this model, water is a "national good of public use," but water use rights are private property (Guiloff, 2012; Hearne and Donoso, 2014). Thus, Chile is an example of an extreme unitary legal system, as the state has limited power to intervene and promote the maintenance of continental aquatic systems, with minimum environmental protections incorporated belatedly and independent of local ecosystems and a large percentage of water already allocated (OECD – UN ECLAC, 2016). This last situation has led to over-granting of water use rights in many agricultural regions in the central macro zone (30°- 35° S), with consumptive and non-consumptive surface flows of 7,271.932 m^3/s granted (DGA, 2016).

Thus, this study contributes to water-use planning in a region of the Southern Hemisphere that, due to its geographical particularities, exhibits high-value, high-quality agricultural production (Aguilera et al., 2019; Fernández et al., 2018), and where regional fruit exports increased 33% in 2018 and are estimated at 1609.4 MMUS$, in contrast to other agricultural exports, which decreased by 22%, to 8.7 MMUS$ (INE, 2018). These changes are attributed to instances of climate change, droughts and fires (Henríquez et al., 2016), in addition to decreases in sales to China, Brazil and Japan (INE, 2018).

It is therefore a priority to calculate indicators that assess agricultural water demands and allow the impacts of climate phenomena to be quantified and change processes to be interpreted (Lathuillière et al., 2018), through a holistic approach that includes technical, environmental, and socio-economic aspects in an innovative and manner, as achieved by water footprint assessment (Zhang et al., 2018).

Current basin-level water management practices make agricultural production dependent on irrigation type and climate characteristics (Billib et al., 2009; Cortés et al., 2012; Valdés-Pinedaet al., 2016), leading to questions such as the following: What component of the WFagricultural (WF_{blue},WF_{green}, WF_{grey}) explains the greatest water consumption? Does the area in which crops are grown influence the water requirement? Is it possible to determine the differences in agricultural water consumption as a function of local climate variability? What percentage of water consumption of crops is given by WF_{blue}, WF_{green} and WF_{grey}?

The hypothesis is that the greatest $WF_{agricultural}$ will occur in dry periods, even though water resources are diminished then. The primary objective of this study is to determine the water consumption of the main crops produced in a central Chilean river basin by calculating the water footprint of agriculture considering climate variability (dry, wet and normal years) and the green, blue and gray water footprint indicators in order to modify future water allocation plans and complement them with more rational water management models.

2. Materials and methods

To analyze the WF, the Cachapoal River basin was selected as representative of a central Chilean basin because it accounts for 78% of the cropland in one of the administrative regions of the area. Agribusinesses are located along its banks, contributing to water pollution (Novoa et al., 2016; Novoa et al., 2019). There is increasing soil erosion (moderate, severe and very severe) in 44% of the total basin area, environmental damage resulting from poor practices in the forestry, farming and livestock sector, which has reduced the area dedicated to cereals and increased the area dedicated to forestry, fruit and grapevines (Donoso et al., 2016). Productivity and yields of some crops have increased, mainly due to the use of agrichemicals and better irrigation techniques (Billib et al., 2009; Jaramillo and Destouni, 2015). However, the water deficit has restricted irrigation water availability (Cortés et al., 2012; Sánchez and Carvacho, 2013).

2.1. Study area: Cachapoal River basin

The Cachapoal River basin (34°S 70°W) spans a surface area of 6,370 km^2 and has a length of 170 km, covering 18 communes with a total of 584,000 inhabitants, 30% of whom work in agriculture-related activities. It has a temperate mediterranean climate with variations due to the topography and drastic thermal and rainfall modifications generated by the relief. The Cachapoal River rises from the Andes Mountains, ends at the Rapel reservoir in the Central Valley and is fed by many streams. It flows past the city of Rancagua (population 240,000) and is used to water crops located in both flat and steep areas, runs through the igneous and sedimentary rocks located in the Central Valley and traverses the Coastal Range (Fig. 1). The rainfall regime of the basin is pluvio-nival, with the greatest streamflows occurring in rainy periods in winter and snowmelt periods in spring-summer and maximum streamflows in the months of June, July and December (Ortiz-Gómez et al., 2015).

The $WF_{agricultural}$ in the Cachapoal basin was determined using the following administrative division of the basin: 1st section, upper basin (34°45’31 S- 70°45´24 W); 2nd section, middle basin (34°17’30 S-71°04´52 W); and 3rd section, lower basin (34°17’29 S-71°24´24 W) (Fig. 1). In addition, agricultural information such as cultivated area, crop type and irrigation techniques in the different basin sections, which was obtained from the agricultural census (INE 2007), was used (Table 1). Agricultural land use is currently expanding only to the lower, southern section of the basin (Fig. 1), a total area of approximately 100 hectares, which accounts for less than 1%

of the area analyzed in this work (Zhao et al., 2016); therefore, the data from 2007 that were used in the analysis are representative of current conditions.

The meteorological input data were obtained from 9 meteorological and rainfall stations maintained by the General Water Directorate (DGA, for its initials in Spanish) (DGA 2016), with homogeneous data over 34 years. Three conditions were covered: wet year (2005), normal year (2006) and dry year (2007), according to previous estimates in Novoa et al. (2016), in which climatic variability was determined with the Mass Curve method and rain behavior by means of box plots, an analysis that provides information on the behavior of seasonal cycles and extreme values in the observations (Guenni et al., 2008). Then the years were classified using the percentile method that defines 5 categories: very dry (0-20th percentile), dry (20-40th percentile), normal (40-60th percentile), wet (60-80th percentile) and very wet (80-100th percentile), as described by (Valiente, 2001), in order to establish thresholds by calculating quintiles, which consists of dividing the distribution of rainfall events over an extended time period into 20% intervals with reference values from the rainfall series in order to establish the climatic reality of the study area.

2.2. Agricultural water footprint

The calculation of the $WF_{agricultural}$ included climatic variables with geo-referenced information such as total and effective precipitation, temperature, solar radiation, wind, insolation, reference evapotranspiration and humidity, as well as soil properties, according to the type of soil, such as moisture, infiltration rate and root depth. In addition, crop data extracted from the Agricultural Studies and Policies Office (ODEPA, 2013) such as Kc values, stages, and critical depletion fraction by development period, along with estimates of crop evapotranspiration and irrigation requirements, were used.

The methodology proposed by Hoekstra et al. (2011) was employed, and the green, blue and gray components of the analyzed crops considered. Where:

$\mathrm{WF_{agricultural}}\ (\mathrm{m^3\ t^{-1}}) = \Sigma \mathrm{WF_{crops}}$ (1)

$\mathrm{WF_{crops}}\ (\mathrm{m^3 t^{-1}}) = \Sigma \mathrm{WF}_{green} + \mathrm{WF}_{blue} + \mathrm{WF}_{gray}$(2)

2.2.1. Green and blue water footprint of crops

Both the green (WF_{green}) and blue water footprints (WF_{blue}) of the crops were determined using the following equations:

$$\mathrm{WF_{green}} = \frac{CWU_{green}}{Y}\,[\mathrm{m^3 t^{-1}}]\ (3)$$

$$\mathrm{WF_{blue}} = \frac{CWU_{blue}}{Y}\,[\mathrm{m^3 t^{-1}}]\ (4)$$

Where: Y ($t\ ha^{-1}$) = crop yield in each section of the basin (Table 1), and CWU_{green}-CWU_{blue} ($m^3\ ha^{-1}$) = green and blue crop water use.

2.2.2. Crop yield estimation

The analyzed agricultural crops were adjusted using the CROPWAT program, which related the evapotranspiration reduction to a yield reduction percentage through the following calculation:

$$\left(1 - \frac{Y_a}{Y_m}\right) = K_y\left(1 - \frac{ET_{caj}}{ET_c}\right)(5)$$

Where: *Ky* is the productivity response factor, ET_{caj} is the adjusted (actual) crop evapotranspiration (mm month^{-1}), ET_c is crop evapotranspiration in standard conditions (without water stress), Y_a is the actual obtained or adjusted crops yields (t ha^{-1}) and Y_m is the expected yields (t ha^{-1}) (Turral et al., 2011).

2.2.3. *Crop green and blue water use*

To calculate CWU_{green} and CWU_{blue}, which are expressed in m^{3}ha^{-1}, the following relationships were used:

$$\mathrm{CWU_{green}} = 10 \text{ x } \sum_{\mathrm{d=1}}^{\mathrm{lgp}} ET_{green} \text{ [volume area}^{-1}\text{]} \quad (6)$$

$$\mathrm{CWU_{blue}} = 10 \text{ x } \sum_{\mathrm{d=1}}^{\mathrm{lgp}} ET_{blue} \text{ [volume area}^{-1}\text{]} \quad (7)$$

Where: Σ: crop growth cycle, that is, from sowing (day 1) to harvest, Igp: length, days in each stage of the cycle and ET_{blue}: blue water evapotranspiration (mm month^{-1}). The factor 10 is meant to convert water depths in millimeters into water volumes per land surface area in m^3/ha.

2.2.4. *Green and blue water evapotranspiration of crops*

The water demand of the crops was determined from the crop water requirement (CWR) using CROPWAT 8.0 software. Under ideal growing conditions, it is assumed that crop water requirements are fully met, such that actual crop evapotranspiration (ETc) will be equal to the crop water requirement: ETc = CWR. The ETc calculation was performed according to the irrigation requirement (IR). This methodology assumes that losses due to irrigation remain and return to the basin. The sum of both ET_{green} (mm year^{-1}) and ET_{blue} (mm year^{-1}) is equal to ET_c (mm year^{-1}). ET_{blue} and ET_{green} were estimated from:

$$ET_{blue} = IR \text{ [mm month}^{-1}] \quad (8)$$

$$IR = ET_C - Peff \text{ [mm month}^{-1}] \quad (9)$$

$$ET_{green} = ET_C \text{ -IR [mm month}^{-1}] \quad (10)$$

Where effective precipitation (Peff) was calculated by the program according to the USDA S.C. method; when the effective rainfall is greater than the total crop evapotranspiration, ET_{blue} is equal to zero. ETc was estimated with a ten-day time step and over the entire growing season, using the following equation:

$$ET_c[\text{mm } year^{-1}] = ET_c[\text{mm } month^{-1}]\text{*months in each year} \quad (11)$$

$$ET_c = Kc * ET_O \text{ [mm month}^{-1}] \quad (12)$$

Where Kc = crop coefficient, which incorporates crop characteristics and averaged effects of evaporation from the soil, ETo = reference evapotranspiration (mm month^{-1}), which was calculated with the CROPWAT 8.0 program using the Penman-Monteith method and climate data based on the latitude and analyzed period obtained from the DGA (2016).

2.2.5. Gray water footprint of crops (m^3 month^{-1})

The WF_{gray} is defined as the volume of freshwater that is required to assimilate the pollutant load based on natural background concentrations and existing environmental water quality standards (Hoekstra et al., 2011), expressed as:

$$\text{WFgray} = \frac{\frac{(\alpha * AR)}{(Cmax - Cnat)}}{\text{Y}} \left[m^3\ \text{t}^{-1}\right] \quad (13)$$

The gray component of the water footprint (WF_{gray}) of crops was calculated as the fertilizer application rate in the field per hectare (AR, kg/ha) times the leaching-runoff fraction (α), expressed as a percentage, divided by the maximum acceptable concentration (cmax, kg m^3), defined by quality standards, minus the natural concentration of the pollutant considered (cnat, kg m^3) and then divided by crop yield, formulated as fertilization time per hectare of crops (Y, t).

The agent used to measure the WF_{gray} was nitrogen, with (AR) being the reference dose of nitrogen for each agricultural crop in the region, taken from ODEPA (2013). The leaching fraction for this agent was 10% and the C_{max} was 0.015 kg m^3, based on DS. 90 of the Chilean Issuance Standard. The C_{nat} of the Cachapoal River basin was established at 0.00001 kg m^3 by evaluating the best-case scenario according to the methodology of Hoekstra et al. (2011).

2.3. Apparent water productivity

According to Salmoral et al. (2011), apparent water productivity (AWP) is the economic value of agricultural production per cubic meter of water used. It is calculated from:

$$\text{PAA} = \frac{\sum(\text{Pr x T}_\text{I})}{WF_{crops}} (14)$$

Where: AWP = apparent water productivity ($/$m^3$) in Chile in the analyzed years, Σ (Pr x T) = market price ($/ton) of the agricultural products, WF = water footprint of the agricultural products (m^3/ton). The AWP values in Chile in the analyzed years were taken from the Regional Exports Report (ODEPA 2013) and reported Central Market prices.

3. Results

3.1. Agricultural water footprint

The analysis of the climatic behavior of the Cachapoal River basin in the 34 years studied and at the weather stations selected as a reference showed that precipitation and effective precipitation revealed higher values in 2005 (representative of a wet year), with 969± 3.1 mm and 625 ± 8.1 mm, respectively. The opposite was observed in 2007 (representative of dry conditions), in which precipitation (420 ± 3.4 mm) and effective precipitation (212 ± 8.2 mm) were lower, with a decrease of 43% compared to 2005. In addition, normal rainfall conditions were recorded in 2006, with average precipitation of 854.5 ± 8.9 mm. The correlation between these variables was linear ($r = 0.99$; $p < 0.05$), with greater rainfall volumes in the upper basin (cordillera section), with a mean of 1,051 ± 123 mm, compared to the middle basin, in which average precipitation of 644.4 ± 53.6 mm was recorded, and the lower basin (under a coastal influence), which presented lower annual precipitation, with 548 ± 40.7 mm (Fig. 3).

Reference evapotranspiration (ETo) remained similar over the years of the study and among the segments of the Cachapoal River. The greatest ETc, in addition to high irrigation requirements (16.116 mm), was estimated in 2007. These values were greater in the lower basin and are linearly correlated ($r = 0.98$; $p < 0.05$) (Fig. 3).

The $WF_{agricultural}$ of the crops grown in the Cachapoal River basin was estimated at 15,902 $m^3\ t^{-1}$in the wet year (2005), 14,091 $m^3\ t^{-1}$in the normal year (2006) and 18,221 $m^3\ t^{-1}$in the dry year (2007). The lowest $WF_{agricultural}$, in 2006, was a result of lower WF_{blue} and WF_{gray}. In addition, compared to a normal year, the $WF_{agricultural}$ in a wet year was greater by 1,810 $m^3\ t^{-1}$

and in by 4,129 m^3 t^{-1} in a dry year; the greatest water consumption occurred in a dry year. The $WF_{agricultural}$ was greater in the middle and lower basin (Figs. 3 and 8).

3.1.1. Green, blue and gray water footprint

The greatest basin-wide WF_{green}, 2,000 m^3t^{-1}, was observed in 2006 (normal) and was related to an increase in the consumption of this water flow due to the fact that the necessary precipitation and humidity for crop growth would have been available in the soil, with climate variables, i.e., temperature, humidity, soil moisture, wind, insolation and radiation, promoting greater crop water consumption and thus increasing ET_{green} to 2,884.4 mm/crop growing period, compared to the wet year, in which ET_{green} was 1,745.8 mm/growing period.

The greatest WF_{blue}, 12,000 m^3t^{-1}, was observed in 2007 (dry year) and was directly correlated with crop irrigation requirements ($r = 0.99$; $P < 0.05$) and the need to reduce the impact of frosts, with most consumed blue water coming from underground sources, since surface sources are in a diminished state (ODEPA, 2013). Significant overall basin consumption in 2005 (wet) was also calculated, with a WF_{blue} of 9,755 m^3t^{-1}, correlated directly with precipitation ($R^2= 0.97$; $P < 0.05$) (Fig.3). In addition, the greatest WF_{blue} was estimated in the middle and lower basin, with amounts of 3,600 ± 137 and 3,540 ± 94, respectively.

The greatest WF_{gray}, 4,934 m^3t^{-1}, was found in 2007 (dry); this amount is 35% of the $WF_{agricultural}$, correlated directly with crop yield and nitrogen use in fertilizers ($R^2 = 0.97$; $P < 0.05$). Average nitrogen application was estimated at 375 ± 35.4 kg ha^{-1}, for a leaching rate of 10%, with a high ± s.d. according to the crop and management system. The water necessary to assimilate nitrogen leaching in the basin is estimated at 1,550 m^3t^{-1} on average in the best-case scenario, for a natural concentration of 0.001 kg m^{-3} (Liu et al., 2012) (Fig.3).

The average water footprint (± s.d.) showed that the $WF_{agricultural}$, WF_{blue} and WF_{gray} decreased in the normal year (2006) and increased in the dry year (2007); the latter year was the beginning of the dry period in Chile, which has continued to the present. In the basin section analysis the average $WF_{agricultural}$, WF_{blue} and WF_{gray} (± s.d.) decreased in the upper basin (Fig.4), despite the fact that the greatest amount of agricultural land was found there, totaling 26,111 ha (Fig. 2), a significant portion of which (65 %, or 17,030 ha) is used for apple, peach and grape crops, which have a low WF_{crop}, as explained in 3.1.3.

3.1.2. Crop yield estimation

The greatest crop yield decreases as a function of climate variables were observed in 2007 and 2005 (14 ± 0.9 % y 13 ± 0.9 %), respectively, and were related to the reduction in evapotranspiration. Avocadoes and peaches were the most affected, the yields of which decreased by 30 ± 1.6 % and 15 ± 1.6 %, respectively. The least affected crop was onions, the yield of which presented a decrease of 3.3 ± 1.6 % (Table 1).

Three crop stages and corresponding coefficient values (Kc) are considered in the Cachapoal River basin: initial, development-growth and final in the 2005, 2006 and 2007 periods (Fig. 5). It is important to stress that for the various agricultural crops the length of the season (growing period) and the crop start date are variables that significantly influence evapotranspiration, as they are directly related to the water needs of each crop ($r = 0.89$; $P < 0.05$), which in turn are affected by climate variability (Hoekstra, 2012; Boisier et al., 2016; Valdés-Pineda et al., 2016).

3.1.3. Crop water footprint

The greatest WF_{crop} values were observed for avocados (1,480 ± 19.2 m^3t^{-1}), olives (1,257 ± 4.1 m^3t^{-1}), corn (750 ± 4.5 m^3t^{-1}) and grapevines (420 ± 14.9 m^3t^{-1}), while the lowest (36 ± 6.4 m^3t^{-1}) was observed for onions (Fig. 6, 8).

The crops with the greatest WF_{green} were olives (196 ± 7.7 m^3 t^{-1}) and avocadoes (156 ± 7.4 m^3 t^{-1}). Meanwhile, the crops with the greatest WF_{blue} were avocadoes (1035 ± 12.3 m^3t^{-1}), olives (751 ± 10.4 m^3t^{-1}), corn (340 ± 11.3 m^3t^{-1}) and grapevines (267 ± 10.5 m^3t^{-1})(Fig. 6, 8).

The greatest WF_{gray} levels were calculated for corn (387 ± 6.6 m^3t^{-1}), olive (310 ± 6.4 m^3t^{-1}) and avocado crops (285 ± 6.1 m^3t^{-1}). The crops with the greatest ET_c consumption and irrigation requirements were estimated to be apples (822± 15.4 m^3 $t^{-1}$and 715 ± 13.2 m^3 t^{-1}) and peaches (815 ±14.7 m^3 t^{-1} and 718 ±16.3 m^3 t^{-1}) (Fig. 6).

3.2.Apparent water productivity

AWP fluctuated according to market prices and the WF_{crop}, resulting in an average of \$135/m^3 in 2005, \$152/m^3 in 2006 and \$130/m^3 in 2007. Onions were the crop with the greatest AWP in 2007 (dry), with \$1,280/m^3, while corn had the lowest AWP, with \$44/m^3 in 2005 (wet) (Fig. 7).

4. Discussion

The study of the water footprint on a drainage-basin scale is carried out through the development of increasingly complex indicators, allowing a large variety of factors that determine the water cycle to be considered and their dynamics to be simulated, in addition to permitting spatial variations to be included as input data (Chukalla et al., 2018; Vanham et al., 2018). Multiple climate variables, soil characteristics and crop properties, as well as evapotranspiration estimates and irrigation requirements, were included in the analysis.

In the 69,433 hectares in which the main crops of the Cachapoal River basin are located, it was established that during the 2005-2007 period avocadoes, olives, corn and grapevines were the crops with the greatest WF_{crop}, due primarily to the amount of water used for their growth and photosynthesis. The onion crops presented the lowest WF_{crop}.

The greatest $WF_{agricultural}$ and WF_{blue} were estimated in the year under drought conditions, as was observed in the northeast of Thailand, where an increase in the WF_{blue} to meet future crop evapotranspiration demands was projected (Shrestha et al., 2017), or in the Upper Litani basin, Lebanon, where the WF_{blue} in summer was greater despite the lower availability of water (Nouri et al., 2019); these two countries, different in terms of hydrological behavior, exhibit similar water consumption projections, but different responses to secure water. The greatest WF_{green} was identified in the normal year, related to climatic conditions that promoted the greatest ET_{green}. WF_{gray} was directly correlated with crop yield. It has been suggested that the combination of precision agriculture and soil conservation tillage systems can reduce the WF_{gray} by 10% (Borsato et al., 2018).

The results showed that climate variations determined the water requirements of the agricultural activity in the basin, as they relate the water flow ($WF_{agricultural}$) to the various forms of consumption, a trend also described in Harris et al. (2014) and Chouchane et al. (2018). It was estimated that in the wet year the WF_{green} accounted for 9%, the WF_{blue} for 61% and the WF_{gray} for 30%, while in the normal year WF_{green} accounted for 15%, the WF_{blue} for 55% and the WF_{gray} for 30% and in the dry year the WF_{green} accounted for 7%, the WF_{blue} for 66% and the WF_{gray} for 27%. These percentages could still be exacerbated by climate change pressure on the water supply and agroecological systems (Shrestha et al., 2017); it has been evidenced that high temperatures, increased evapotranspiration, variable precipitation, floods and droughts affect crop yields and growth, shortening phenological phases (sowing, flowering and harvest) (Gregory et al., 2005; Teixeira et al., 2013; Boonwichai et al., 2019)

Average agricultural water footprints around the world differ significantly among crops and regions; it is expected that crop yields will increase at higher latitudes and decrease at lower latitudes (Stocker et al., 2013). However, to better understand the calculated water footprint in the Cachapoal River basin, it can be stated that it is below the global average according to Mekonnen and Hoekstra (2011), due mainly to superior agricultural performance (Fig. 8).

In addition, it is reported that crop water requirements are greater in Latin America (Aldaya et al., 2010; Chartzoulakis and Bertaki, 2015) than in Asia (Konar et al., 2011), but that the water footprint of the crops is lower, a situation that must be taken into account regarding production activities, export costs and water productivity increases (Fig. 6).

To overcome the scarcity of water necessary for agriculture, both water efficiency and the climate situation must be considered. For example, the feasibility of using marginal water such as treated wastewater or drainage water for irrigation should be assessed (Dong et al. 2013; Iglesias and Garrote, 2015). A notable example is the O'Higgins Region, which, driven by the passage of Law 18,450, has incorporated higher-tech irrigation methods into the production of high-value export products. Nonetheless, this effort has neither resulted in lower water consumption nor incorporated apparent the concept of water productivity, that is, considering the water consumption of the products in their prices.

Water resources management has demonstrated that scenarios (wet, normal and dry), such as those included in this study, are of great significance for explaining the uncertainties and behavior of water consumption associated with climatic and territorial conditions (upper, middle and lower basin). Approaches based on these scenarios have been applied to explore and analyze future water requirement problems (Zhang et al., 2018) and make it possible to assess climate change scenarios (Zhao et al., 2014; Zhang et al., 2017), land-use changes, irrigation technology (Miguel Ayala et al., 2016; Nouri et al., 2019) and agricultural production changes (Liu et al., 2012), as well as to support water managers and provide solutions (Dong et al. 2013; Iglesias and Garrote 2015; Wei et al. 2018).

An essential component in addressing the challenges of water and food security is the generation of knowledge and innovation such as water management methods (Tian et al., 2018), social organization, adequate legal frameworks and development of institutions such as the Superintendent of Water, proposed in the context of the National Policy on Water Resources of 2015.

Thus, maintaining an economic and ecological equilibrium is crucial for sustainable land use. Doing so directly influences the quantity and quality of water resources, the well-being of the population, jobs and poverty levels (Shah et al., 2018). Poor management leads to chaos, but through the assessment of agricultural water consumption, such as that presented in this study, a more rational rights granting scheme can be suggested, as proposed by the European Union, be it an integrated water resources management (IWRM) plan (Ziolkowska and Peterson, 2017), modification of the water code (Dvinskikh and Larchenko, 2018) or the use of an integrated model of water consumption for production, living, and ecology (WPLE) (He et al., 2018).

While Chile has implemented specific public policies regarding management, they have been weak. More than 45 public institutions make water-related decisions and there is a lack of transparency regarding the total of allocated water rights, adequate economic and environmental incentives for efficient use or reuse and restrictions in agriculture that consider the carrying capacity of ecosystems, leading to territorial conflicts due to the inherent scarcity and irrational use of water resources and the discrepancy between water supply and demand.

Due to climate variability, an increase in irrigated agriculture in the Cachapoal River basin is expected; however, irrigation is not sustainable if the water supply is not reliable, necessitating greater efforts to find crops that use minimal water or are less affected by climate variability. In addition, it is essential to develop specific adaptation strategies for each area of the basin by studying changes in planting dates, crop relocation, selection of better varieties, online monitoring and new technologies, irrigation type analysis or irrigated area reduction.

5. Conclusions

Climate variations are determinant in the water requirements of agricultural activities, particularly in a Latin American basin with a mediterranean climate, since the water flow is related to various types of consumption, that is, in a year with drought conditions (this is, 43% decrease in precipitation relative to 34 years of records) the greatest $WF_{agricultural}$ and WF_{blue} were estimated, while in normal conditions the greatest WF_{green} was determined. The WF_{gray}, however, was directly correlated with crop yield.

The $WF_{agricultural}$ of the Cachapoal River basin indicates that there are crops with greater apparent water productivity, *e.g.*, onions and tomatoes, which would be convenient for local drought situations. Although it was established that avocado, olive, corn and grapevine crops have the greatest $WF_{agricultural}$, there is great demand for high-quality offerings of these crops in international markets; therefore, greater attention must be given to water use, irrigation techniques and crop selection.

Water management policies must be focused on integrated basin management, promoting agricultural activity synergy in this basin, in addition to analyzing the advantages and disadvantages of certain crops and prioritizing water sustainability (equity, efficiency) given the foreseeable increased demand for food and irrigable area. These policies must also include a periodic review of the cultivated area and changes in farmland use, along with the establishment of rainfall monitoring and meteorological stations that record important variables such as reference evapotranspiration, humidity and wind direction, thus facilitating data management, the search for indicators and decision making.

Finally, in addition to providing a general orientation for future water allocation decisions in the basin, this study constitutes a significant advance in the use of a new tool for territorial water planning that can serve as a technical foundation for management on the basis of an interpretation of the impacts of blue, green and gray water scarcity, along with changes in water flows, land use and the climate on a rapidly changing agriculture.

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Nomenclature

Symbol	Unit	Explanation
AR	kg/ha / mass/area	Application rate of a chemical (fertilizer or pesticide) per unit of land
A	-	Leaching-run-off fraction, i.e. fraction of applied Chemicals reaching freshwater bodies
AWP	$/m^3	Apparent water productivity
CWU_{blue}	m^3 ha^{-1} / volume/area	Blue crop water use
CWU_{green}	m^3 ha^{-1} / volume/area	Green crop water use

CWR	mm $month^{-1}$ / length/time	Crop water requirement
Cmax	kg m^3 / mass/volume	Maximum acceptable concentration of a chemical in a receiving water body
Cnat	kg m^3 / mass/volume	Natural concentration of a chemical in the receiving water body
ET_{caj}	mm $month^{-1}$	Adjusted (actual) crop evapotranspiration
ET_c	mm $month^{-1}$ / length/time	Crop evapotranspiration (under optimal conditions)
ET_{blue}	mm $year^{-1}$ mm $month^{-1}$ / length/time	Blue water evapotranspiration
ET_{green}	mm $year^{-1}$ mm $month^{-1}$ / length/time	Green water evapotranspiration
ETo	mm $month^{-1}$ / length/time	reference crop evapotranspiration
Igp	-	length, days in each stage of the cycle
IR	mm $month^{-1}$ / length/time	Irrigation requirement
Ky		productivity response factor
Kc	-	crop coefficient
Peff	mm $month^{-1}$ / length/time	effective rainfall
$WF_{agricultural}$	m^3t^{-1} / volume/time	Agricultural water footprint
WF_{blue}	m^3t^{-1} / volume/time	Blue water footprint
WF_{crops}	m^3t^{-1} / volume/time	Crops water footprint
WF_{gray}	m^3t^{-1} / volume/time	Gray water footprint
WF_{green}	m^3t^{-1} / volume/time	Green water footprint
Y	t ha^{-1} / mass/area	Crop yield
Y_a	t ha^{-1} / mass/area	actual obtained or adjusted crops yields
Ym	t ha^{-1} / mass/area	expected yields

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Fig. 1 Cachapoal River basin. The streamflow gauging stations used in the environmental flow analysis are indicated.

Fig. 2 Summary of agricultural activity information: crop types, cultivated area and irrigation techniques in the Cachapoal River basin, Chile. Source: INE, 2007.

Fig. 3 Cumulative WFagricultural of the Cachapoal River basin. Annual precipitation (Rain), reference evapotranspiration (ETo), effective rain , crop evapotranspiration (ETc) and irrigation requirements (IR) in 2005, 2006 and 2007 and the various sections of Cachapoal River basin are indicated.

Fig. 4 Average water footprints (± s.d.) established in the Cachapoal River basin for (a): wet (2005), normal (2006) and dry (2007) years and the basin sections (b).

Fig. 5 Stages and coefficients (kc) estimated for the crops of the Cachapoal River basin.

Fig. 6 Agricultural water footprint of the crops in the sections of the Cachapoal River basin, a) 2005, b) 2006 and c) 2007.

Fig. 7 Apparent water productivity.

Fig. 8 Summary of the agricultural water footprint in the Cachapoal River basin.

Table 1
Reference yields and percentage of yield decrease according to climate variables, estimated for the crops of the Cachapoal River basin.

cultivo	Yield Ref. (t ha^{-1})	Percentage of yield decrease (%)								
		2005			2006			2007		
		Section			Section			Section		
		Upper basin	Middle basin	Lower basin	Upper basin	Middle basin	Lower basin	Upper basin	Middle basin	Lower basin
Ind. tomato	80	10	11	12	8,5	8,6	9	11,9	12,2	12,4
Tomato	55	10	11	12	8,5	8,6	9	11,9	12,2	12,4
Melon	25	10,8	11,7	11,4	6,6	7,9	7,5	11,5	11,5	11,2
Onion	65	4,6	5,6	4,5	0	0	0	4,3	5,5	5,5
Citrus	28,2	9,6	9,6	10,4	8,4	8,1	8,6	10,3	9,9	10
Apple	45,1	9,6	10,3	10,6	8,4	8,5	8,6	10,3	10,3	10,1
Peach	37,4	16,2	16,9	17,5	11	11,9	12,3	17,5	17,4	17,2
Avocado	9,3	34,4	31,6	45,9	8,1	8,2	9,1	48,3	47,1	45,8
Grape	24,5	8,2	8,8	8,9	5,2	5,5	6,2	8,8	8,6	9,1
Olive	4,7	9,9	10,9	10	5	5,5	5,7	9,3	9,8	9,3
Corn	11,6	12	13,1	9,2	6	6,4	6,5	13,5	14	15,1
Average decrease (%)		12,3	12,8	13,9	6,9	7,2	7,5	14,3	14,4	14,4

Highlights

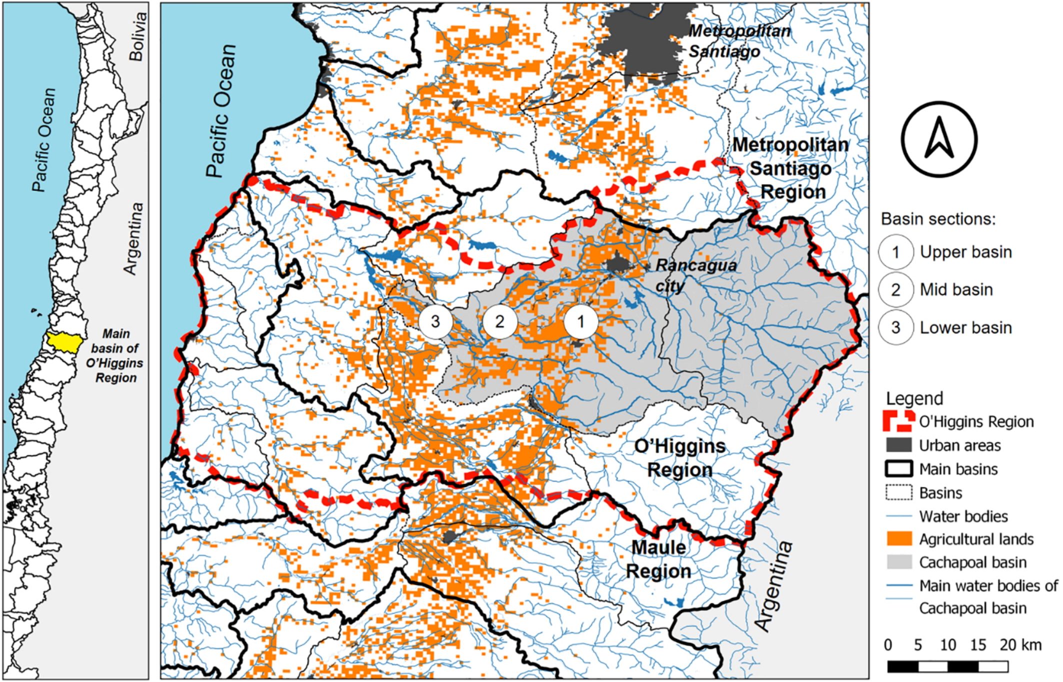
1. Basin-scale agricultural water consumption was assessed considering climate variability.

2. A geographic variable (upper, middle, lower basin) was added to identify local changes.

3. The $WF_{agricultural}$ WF_{blue} and WF_{gray} were greatest in the dry year and WF_{green} in a normal year.

4. Avocados, olives and corn had the greatest $WF_{agricultural}$, in contrast to onions.

5. The integration of these results would allow rational water allocation.



Pacific Ocean
Bolivia
Argentina
Main basin of O'Higgins Region
Pacific Ocean
Metropolitan Santiago
Metropolitan Santiago Region
Rancagua city
3
2
1
O'Higgins Region
Maule Region
Argentina
Basin sections:
1 Upper basin
2 Mid basin
3 Lower basin
Legend
O'Higgins Region
Urban areas
Main basins
Basins
Water bodies
Agricultural lands
Cachapoal basin
Main water bodies of Cachapoal basin
0 5 10 15 20 km

Figure 1

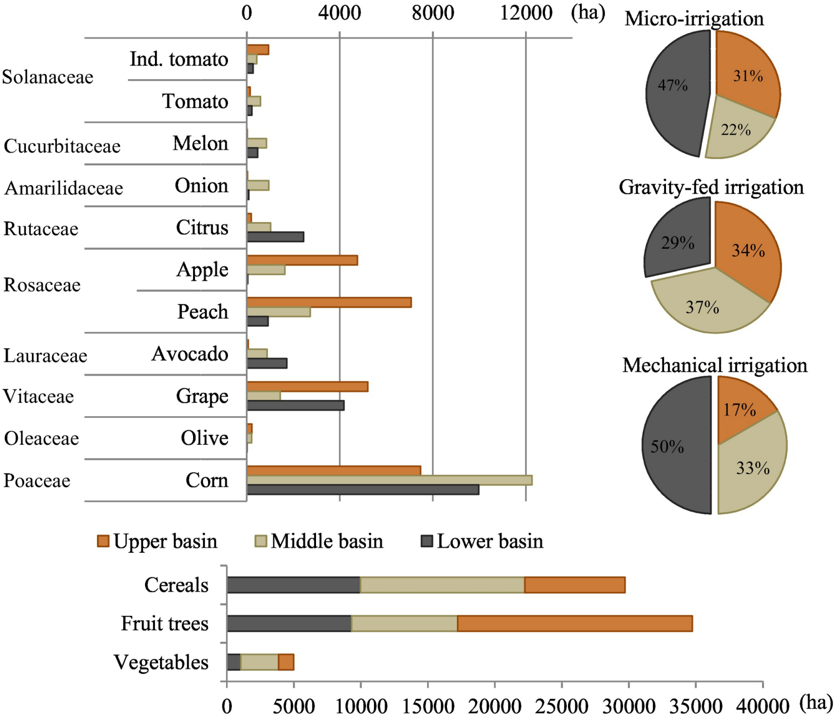

0
4000
8000
12000
(ha)
Solanaceae
Ind. tomato
Tomato
Cucurbitaceae
Melon
Amarilidaceae
Onion
Rutaceae
Citrus
Rosaceae
Apple
Peach
Lauraceae
Avocado
Vitaceae
Grape
Oleaceae
Olive
Poaceae
Corn
Micro-irrigation
47%
31%
22%
Gravity-fed irrigation
29%
34%
37%
Mechanical irrigation
17%
50%
33%
Upper basin
Middle basin
Lower basin
Cereals
Fruit trees
Vegetables
0
5000
10000
15000
20000
25000
30000
35000
40000
(ha)

Figure 2

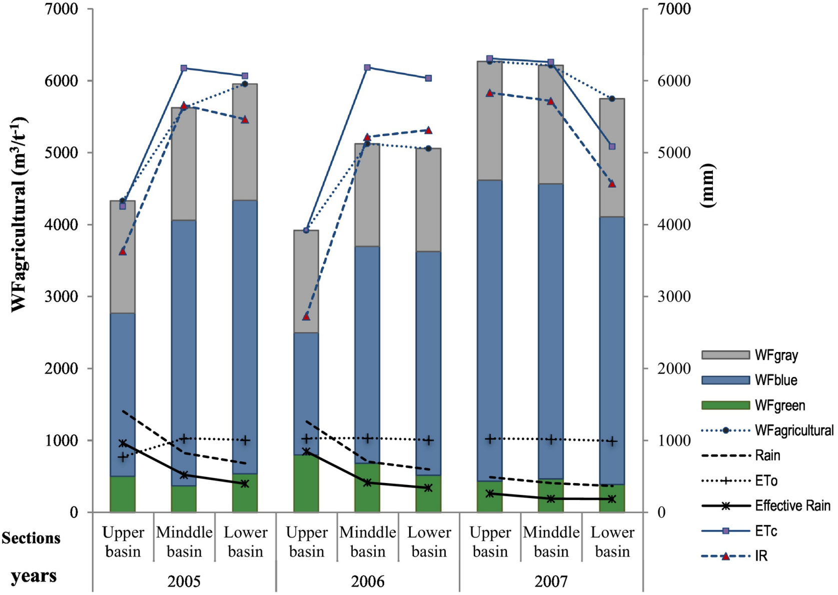
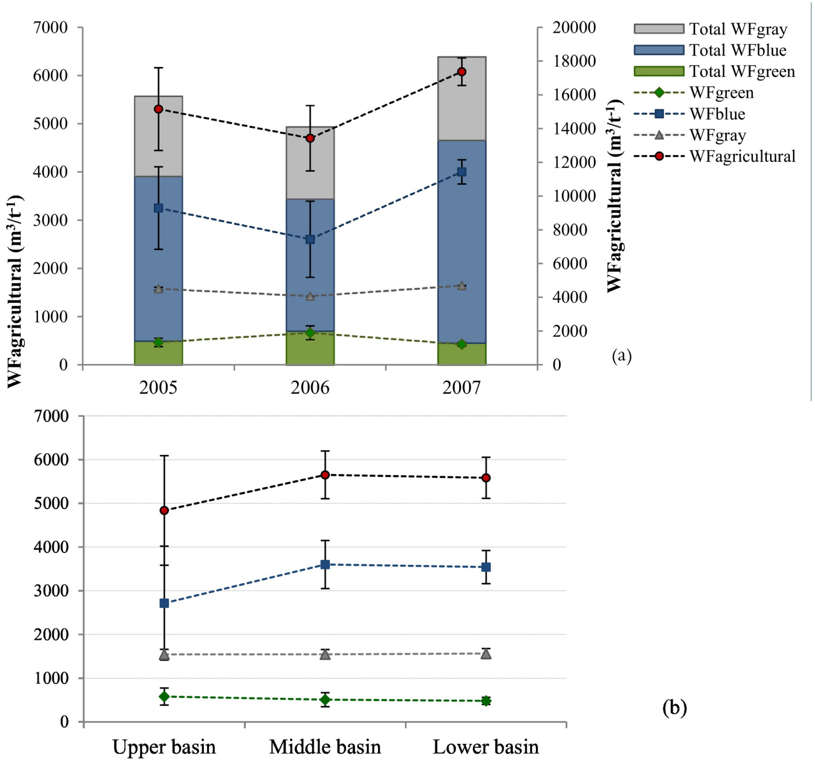
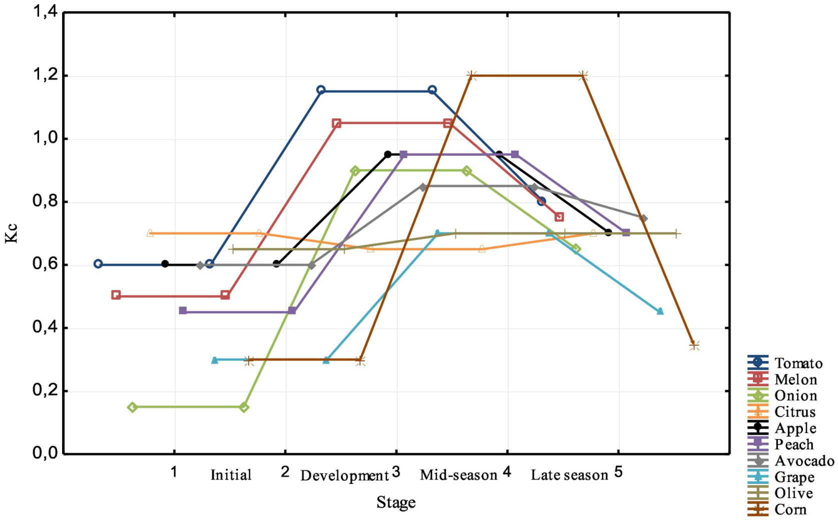

7000
6000
5000
4000
3000
2000
1000
0
WFagricultural (m³/t⁻¹)
(mm)
WFgray
WFblue
WFgreen
WFagricultural
Rain
ETo
Effective Rain
ETc
IR
Sections
Upper basin
Minddle basin
Lower basin
years
2005
2006
2007

Figure 3



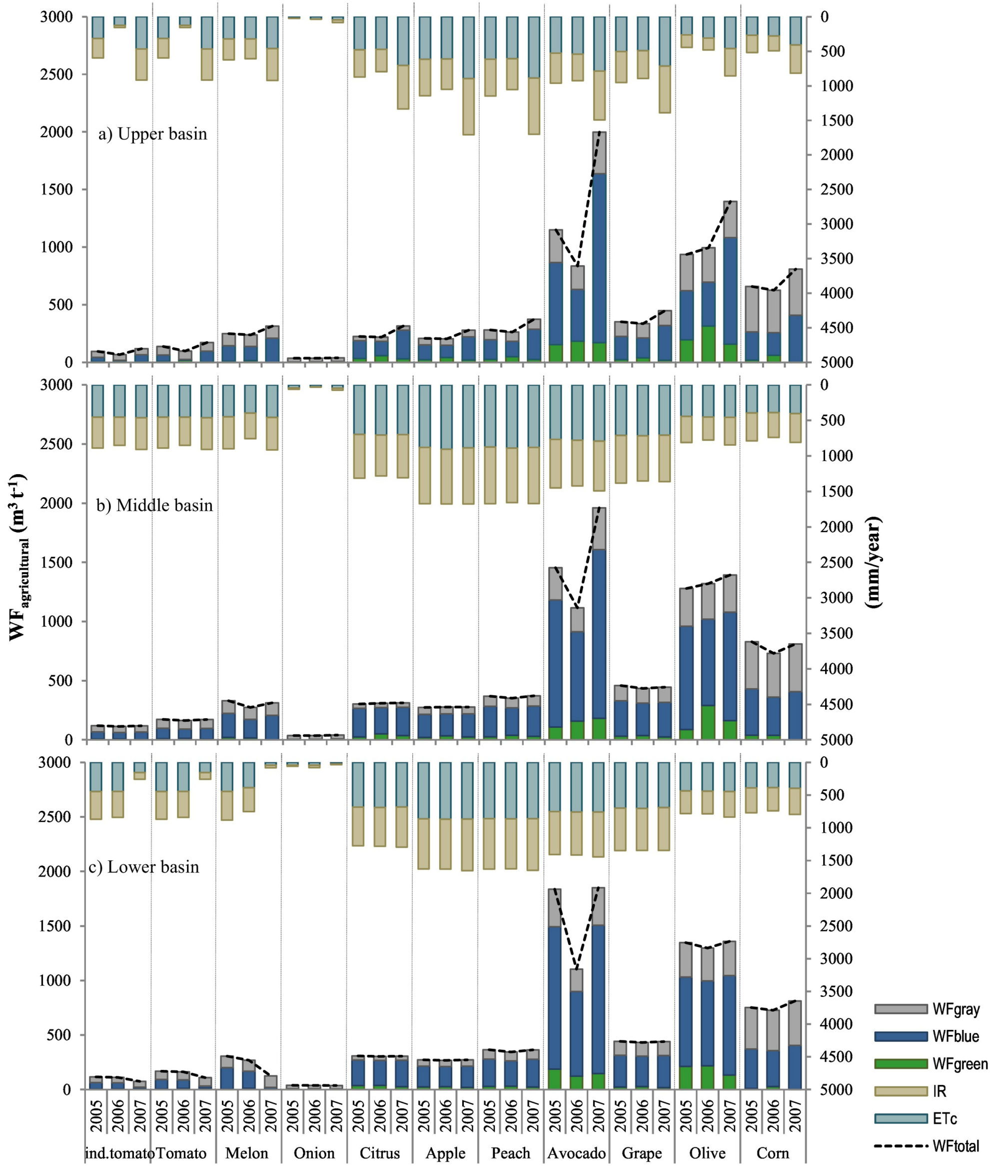
7000
6000
5000
4000
3000
2000
1000
0
WFagricultural (m3/t-1)
20000
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
WFagricultural (m3/t-1)
Total WFgray
Total WFblue
Total WFgreen
WFgreen
WFblue
WFgray
WFagricultural
2005
2006
2007
(a)
7000
6000
5000
4000
3000
2000
1000
0
Upper basin
Middle basin
Lower basin
(b)

Figure 4



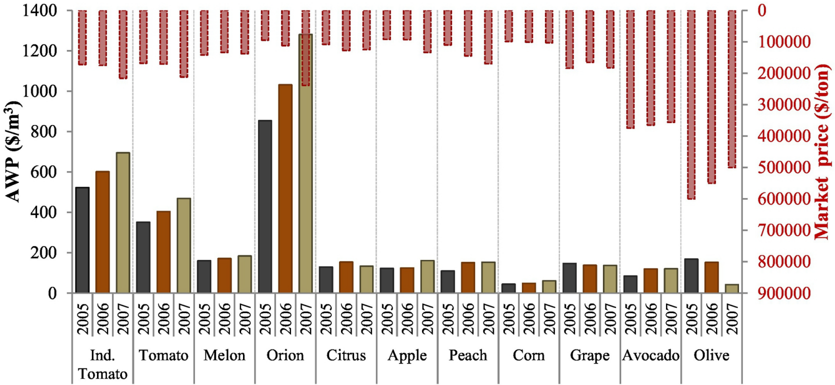
1,4
1,2
1,0
0,8
0,6
0,4
0,2
0,0
Kc
1
Initial
2
Development
3
Mid-season
4
Late season
5
Stage
Tomato
Melon
Onion
Citrus
Apple
Peach
Avocado
Grape
Olive
Corn

Figure 5



a) Upper basin
b) Middle basin
c) Lower basin
WF$_{agricultural}$ (m^3 t^{-1})
(mm/year)
ind.tomato
Tomato
Melon
Onion
Citrus
Apple
Peach
Avocado
Grape
Olive
Corn
2005
2006
2007
WFgray
WFblue
WFgreen
IR
ETc
WFtotal

Figure 6



AWP ($/m³)
1400
1200
1000
800
600
400
200
0
Market price ($/ton)
0
100000
200000
300000
400000
500000
600000
700000
800000
900000
2005 2006 2007
Ind. Tomato
Tomato
Melon
Orion
Citrus
Apple
Peach
Corn
Grape
Avocado
Olive

Figure 7

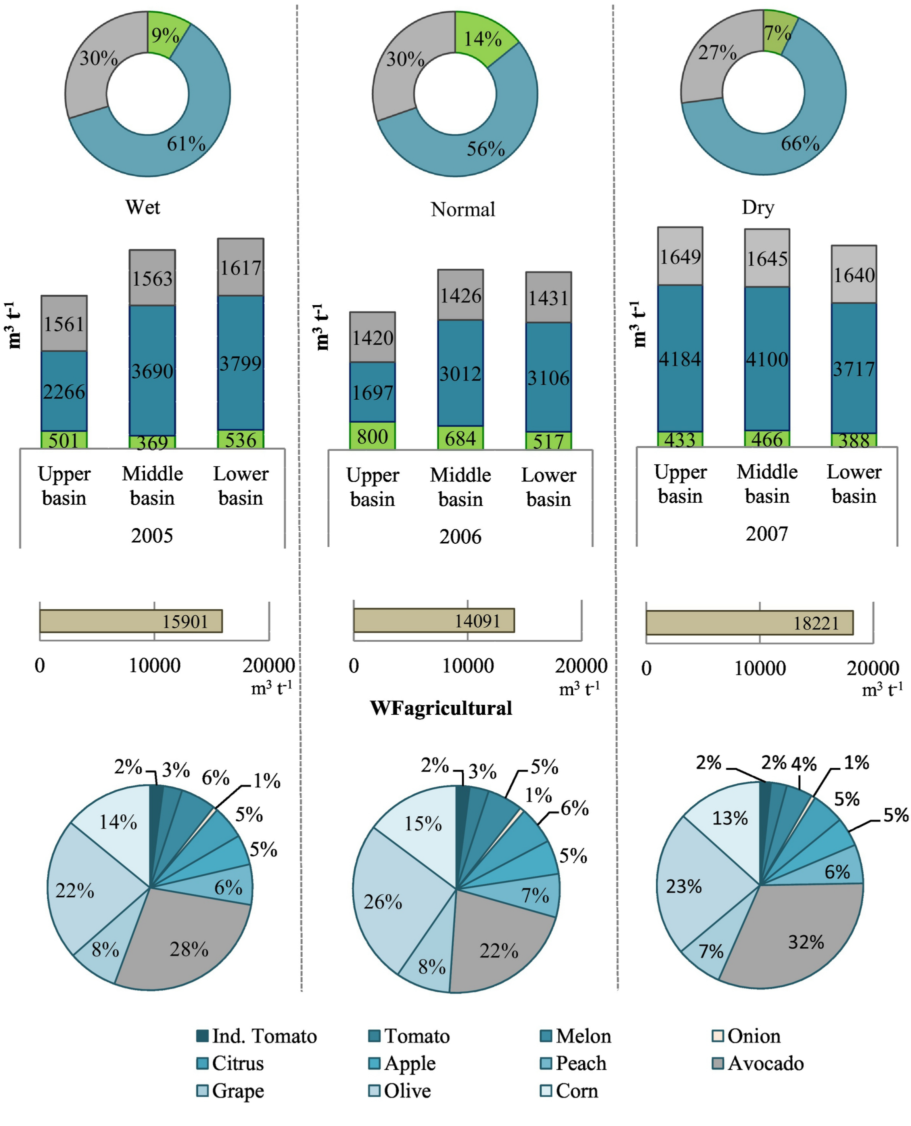

9%
30%
61%
14%
30%
56%
7%
27%
66%
Wet
Normal
Dry
m³ t⁻¹
1561
2266
501
1563
3690
369
1617
3799
536
1420
1697
800
1426
3012
684
1431
3106
517
1649
4184
433
1645
4100
466
1640
3717
388
Upper basin
Middle basin
Lower basin
2005
2006
2007
15901
14091
18221
0
10000
20000
WFagricultural
14%
22%
8%
28%
6%
5%
5%
1%
6%
3%
2%
15%
26%
8%
22%
7%
5%
6%
1%
5%
3%
2%
13%
23%
7%
32%
6%
5%
5%
1%
4%
2%
2%
Ind. Tomato
Tomato
Melon
Onion
Citrus
Apple
Peach
Avocado
Grape
Olive
Corn

Figure 8