Evaluación de la escasez de agua y la sostenibilidad hídrica de la agricultura de regadío en el Valle de Ica, Perú

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CRANFIELD UNIVERSITY

ARACELI VIÑARTA CARBÓ

WATER SCARCITY AND SUSTAINABILITY ASSESSMENT OF IRRIGATED AGRICULTURE IN THE ICA VALLEY, PERU

SCHOOL OF WATER, ENERGY AND ENVIRONMENT
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This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

ABSTRACT

The Ica Valley in Peru has undergone significant agricultural transformation and growth, with current production contributing to approximately one third of the country’s total agro-exports. Agricultural expansion is taking place at the expense of water resources, both surface and groundwater. Uncontrolled groundwater abstractions have led to over-exploitation of the Ica-Villacuri aquifer, the largest groundwater reserve in Peru. This research aimed to assess the irrigation water needs in the Ica Valley and evaluate levels of water scarcity and sustainability of irrigated agriculture. Firstly, the research evaluated the current situation and historical trends in cropped area, the composition of small and large-scale farms, export trade, and water abstractions. Historical and current blue water footprints (WF) were then estimated, distinguishing the water source between surface and groundwater, to assess water scarcity and sustainability through water stress and water debt indicators, respectively. This distinction of WF linked to source was particularly novel since this approach has not previously been applied in Peru. The results show that the groundwater footprint is 1.5 times higher than the surface water footprint. It has been demonstrated that irrigated agriculture in the Ica Valley has potentially a very detrimental effect on water resources (notably groundwater) given the moderate levels of water stress that were estimated. Based on climate conditions and existing cropping patterns from 2017, irrigated agriculture is considered to be locally unsustainable since 8 years are required to replenish the water resources that are typically being consumed by agricultural production in one year. There is thus an urgent need to either increase water availability and/or improve renewability if the current model of agricultural expansion and production is expected to continue. Otherwise, urban supply in Ica and the countries which rely on importing fruits and vegetables from this part of Peru are likely to be significantly negatively impacted.

Keywords:

Abstraction, agro-export, irrigation, groundwater, water footprint

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ABBREVIATIONS

ANA	Autoridad Nacional del Agua (National Authority of Water)
WF	Water Footprint
LCA	Life Cycle Assessment
Y	Yield
ET_{blue}	Blue evapotranspiration
lgp	Length of growing period
AI	Applied irrigation
CPAI	Consumptive part of applied irrigation
ET_a	Actual evapotranspiration
P_{eff}	Effective precipitation
ENA	Encuesta nacional agropecuaria (Agricultural national survey)
Kc	Crop coefficient
WS	Water stress
WD	Water debt repayment time
WR	Water renewability
SDG	Sustainable development goals

1 INTRODUCTION

Globally, the agricultural sector withdraws approximately 70 per cent of all freshwater for irrigation (FAO, 2016). In some regions, this is leading to rapid rates of depletion in both groundwater (Famiglietti, 2014; Wada, Wisser and Bierkens, 2014) and surface water resources (Vörösmarty et al., 2010). In this context, international food trade has been identified as the main driver for rising levels of irrigation demand. Eleven per cent of non-renewable groundwater use is embedded in food exported worldwide (Dalin et al., 2017). Moreover, those exporting regions are often water-stressed, and therefore, water and food securities are at risk, both locally and globally (Dalin et al., 2017; Wada, Van Beek and Bierkens, 2012). This has contributed to classifying water crisis, defined as a reduction in water availability that results in detrimental effects on economic activity and/or human health, as being among the top ten global risks in terms of their likelihood and impact (World Economic Forum, 2019).

1.1 Agricultural expansion in Peru

Peru is an upper middle-income country which has reported an economic annual growth rate of 10% in gross domestic product (The World Bank Group, 2017). This has led to a 150% increase in US dollars linked to export activity since 2007 (WITS, 2017). In the early 1990s, the main export commodities were coffee, sugar and cotton. The latter two have been gradually replaced by high value vegetables including asparagus and onions, and fruits such as grapes and mangoes (Torres-Zorrilla, 2019). The Ica Valley, located in south of Lima, has undergone significant agricultural transformation and growth, with current production contributing to approximately one-third of the country's total horticultural and fruit exports (Oré, 2005).

Whilst having positive impacts on both the economy and employment, agricultural expansion in the Ica Valley has also led to some detrimental effects on water resources although principally on groundwater (Muñoz, 2016; Williams and Murray, 2018). Surface water comes from the River Ica, while groundwater is abstracted from the Ica-Villacuri aquifer, the largest aquifer in Peru which represents nearly half (40%) of the country's groundwater resources (Oré, 2005). Over-abstraction for agricultural purposes has led to rapid groundwater depletion, with annual rates of water table reduction of 4m reported in some parts of the catchment (Zegarra, 2018). This decline in the water table has taken place despite a prohibition on the construction of new wells since 2008 (Oré and Muñoz, 2018)

In the Ica Valley, agricultural activity coupled with a growing population have increased water demand (Damonte and Boelens, 2019), while the natural variability in precipitation and a changing climate have decreased water supplies (Andres et al., 2014). In 2010, this imbalance resulted in the declaration of a water emergency situation (Gobierno Regional de Ica, 2010). Owing to its economic importance and its critical water resource situation, the region has been the focus of many hydrological and hydrogeological studies, whose aims were to quantify the available water resources and to characterise the aquifer and its interconnections with surface water (ANA, 2017; Peña, Sánchez and Pari, 2010). The most common approach used to assess the sustainability of groundwater use has been a comparison between water abstractions and aquifer recharge (ANA, 2017; Cárdenas, 2012; Tahal Consulting Engineers, 1969). Total groundwater recharge is divided into three components: (i) direct recharge from the River Ica, calculated as the losses of river flow between two gauging stations; (ii) direct recharge from leaking distribution channels, calculated applying the same methodology as in the river; and (iii) indirect recharge from irrigated land taking into account the reported irrigated area and water depth (ANA, 2017). There is thus a real lack of robust evidence on understanding the links between irrigated land use (crop types and composition), irrigation needs and aquifer recharge potential.

1.2 Water footprint assessment

Since 2002 the Peruvian government, through the Autoridad Nacional del Agua (ANA), has encouraged sustainable agricultural production using the water footprint (WF) concept (MINAGRI, 2015), initially developed by Hoekstra and Hung (2002). Water sustainability is defined as the fulfilment of the current water demand without compromising future water supplies whilst preserving the environment (Russo, Alfredo and Fisher, 2014). The WF represents the amount of water consumed by a nation or a specific geographical location, by sector, product or company (Water Footprint Network, 2019). The WF in croplands (m^3/ton) is divided into three components: (i) blue WF, which is the surface and groundwater evapotranspired by crops; (ii) green WF, which is the water from precipitation that is stored in the root zone and evapotranspired by crops; and (iii) grey WF, which is the amount of water required to assimilate the pollutants according to the natural water quality. For irrigated agricultural production, the blue and green WFs are particularly relevant (Water Footprint Network, 2019) as combined they refer to the consumptive use of water by crops (Hoekstra, 2013). In arid and semi-arid environments, where precipitation is scarce and agriculture relies almost entirely on irrigation, the green WF can represent less than 10% of the consumptive WF, and therefore, only blue water component can be assessed (Chukalla, Krol and Hoekstra, 2015; Hoekstra et al., 2012; Mekonnen and Hoekstra, 2011). Moreover, recent studies have concluded that splitting blue water into surface and groundwater is appropriate owing to their differences in access, reliability and availability (Rezaei Kalvani et al., 2019; Tuninetti, Tamea and Dalin, 2019).

The blue WF in agriculture is usually used to develop indicators that characterise the degree of water scarcity or sustainability. Water scarcity can be evaluated through the use of a water stress index, which is defined as the ratio between the volumetric water footprint and water availability (Xinchun et al., 2017). Water sustainability can be evaluated through the water debt indicator, which is calculated as the volumetric water footprint divided by the renewable volume of water (Tuninetti, Tamea and Dalin, 2019). Both indicators have the advantage that they can be split into surface and groundwater, thus highlighting which resource is most stressed or in an unsustainable situation (Rezaei Kalvani et al., 2019; Tuninetti, Tamea and Dalin, 2019).

There are very few previous studies that have assessed the agricultural WF of irrigated production in Peru. At a national scale, the agricultural WF of the main crops grown in the region has been assessed by MINAGRI (2015) and for specific crops including asparagus (Fonseca, Verano and Mariluz, 2012a) and rice (Fonseca, Verano and Mariluz, 2012b). At a regional scale, the WF for grape production was estimated within the Ica Department using a Life Cycle Assessment (LCA) (Vázquez-Rowe et al., 2017). None of these studies have explicitly focused on the Ica Valley or emphasised the importance of an arid climate in distinguishing surface and groundwater in sustainability assessments in irrigation water management. Therefore, there is a lack of attention to evaluate from a crop-specific approach the water consumed in irrigated croplands in the Ica Valley focusing on the source of the water and to analyse the status of sustainability and water scarcity of the irrigated agriculture.

1.3 Aim and objectives

This aim of this thesis was to assess the irrigation needs in the Ica Valley (Peru) and evaluate levels of water scarcity and the sustainability of irrigated agriculture. In order to understand the current water-related challenges linked to agricultural expansion, the first objective focussed on evaluating historical trends in cropped area, the composition between small and large-scale farms, and trends in agro-export trade and water abstraction. The second objective was to analyse the historical and current blue water footprints for the case study region considering historical yields and the current spatial extent of irrigated land, respectively. The third objective was to estimate current water scarcity and the sustainability of irrigated agriculture using defined indicators, and through future plausible scenarios, based on blue water use by crops, to assess future changes in water renewability and water availability.

2 MATERIALS AND METHODOLOGY

This desk-based research was carried out in three stages. Firstly, it commenced with a literature review to understand the links between the agricultural sector and water-related challenges. A combination of published statistics and data were compiled to analyse historical trends in irrigated area, agricultural production, export trade and groundwater abstractions. Secondly, the blue WF was estimated, distinguishing the source of irrigation water between surface and groundwater. This distinction in WF depending on source has not previously been applied in Peru. The approach to estimate the WF used the WaSim model (Hess, Harrison and Counsell, 2000), which estimates the soil water balance including inputs of rainfall and irrigation and outputs of crop water use, runoff and deep drainage (recharge), on a daily time-step. Thirdly, water scarcity and sustainability were assessed through the water stress index and an adapted water debt indicator, respectively. The method was developed and applied to a specific case study region, the Ica Valley, which is briefly described below. Finally, future plausible scenarios were evaluated to predict the water scarcity and sustainability assessment for the near future (2030).

2.1 Study area

The Ica Valley is located in the Ica Province, within the Ica Department, which is in the central and occidental Peruvian territory (Figure 2-1). The reported population in the Ica Department in 2017 was around 850,000 (INEI, 2017a). Due to agricultural expansion, Ica is an attractive area for immigration due to work opportunities, resulting in a low poverty index with almost zero unemployment (INEI, 2018).

Although this study was focused on the Ica Valley, it is important to understand its context within the River Ica basin and its interconnection to the Ica-Villacuri aquifer. The River Ica, which rises at 4500 m.a.s.l. in the Andean mountains of Huancavelica, runs through Ica Valley, and finally flows into the Pacific Ocean. The natural basin has an area of 7188 km^2; water flows were increased in 1959 by the Choclococha system which is a network of lakes and channels that transfers water from the Amazon basin, characterised by a wetter climate, to the River Ica basin. The Ica-Villacuri aquifer consists of sandy-clayey and sandy-silty porous media, which provides rapid infiltration; and the geology has a high capacity for water retention. It has been reported that 94% of the soils are suited to irrigated agriculture (Oré, 2005). The river and the aquifer are interconnected. The main source of the river flow comes from rainfall in the Huancavelica Department, and in turn, the river is reported to be the main source of recharge to the aquifer (Peña, Sánchez and Pari, 2010). For example, aquifer recharge in 2017 was estimated to be 266 Hm^3 with over half (55%) of that recharge coming from the River Ica (Peña, Sánchez and Pari, 2010).

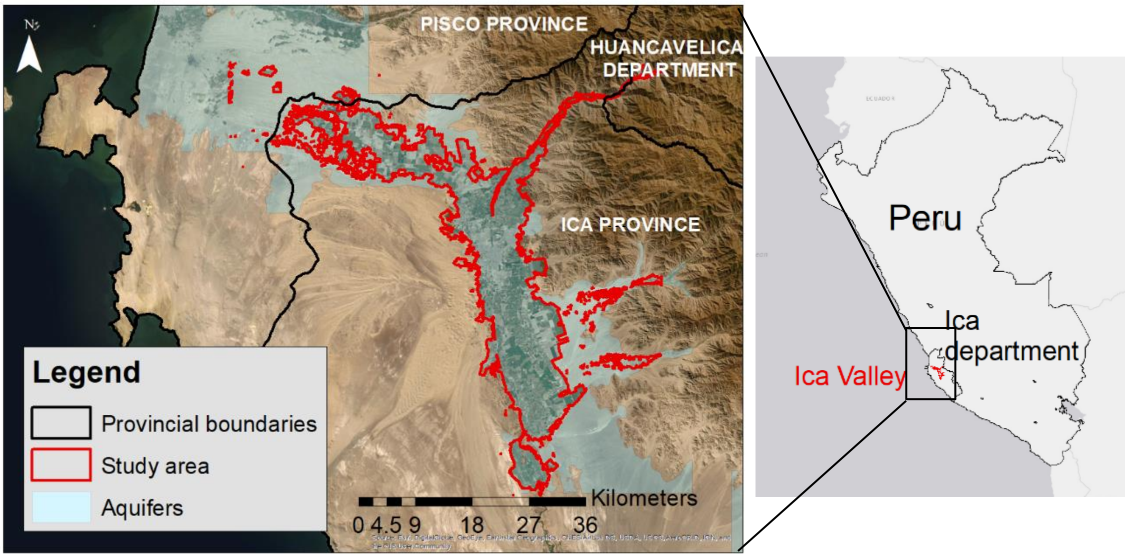


Figure 2-1. Location of Ica Valley, within the Ica Province and Ica Department.

The agroclimate in the region is typically warm and dry all year (Figure 2-2), characteristic of a desert climate. The summer temperature, from January to April, is above 30 Celsius degrees. In autumn, winter and spring the average temperature ranges between 18 and 21 degrees. The Ica Valley can be classified as a hyper-arid zone (FAO, 1989) with a mean annual precipitation of almost 10 mm.

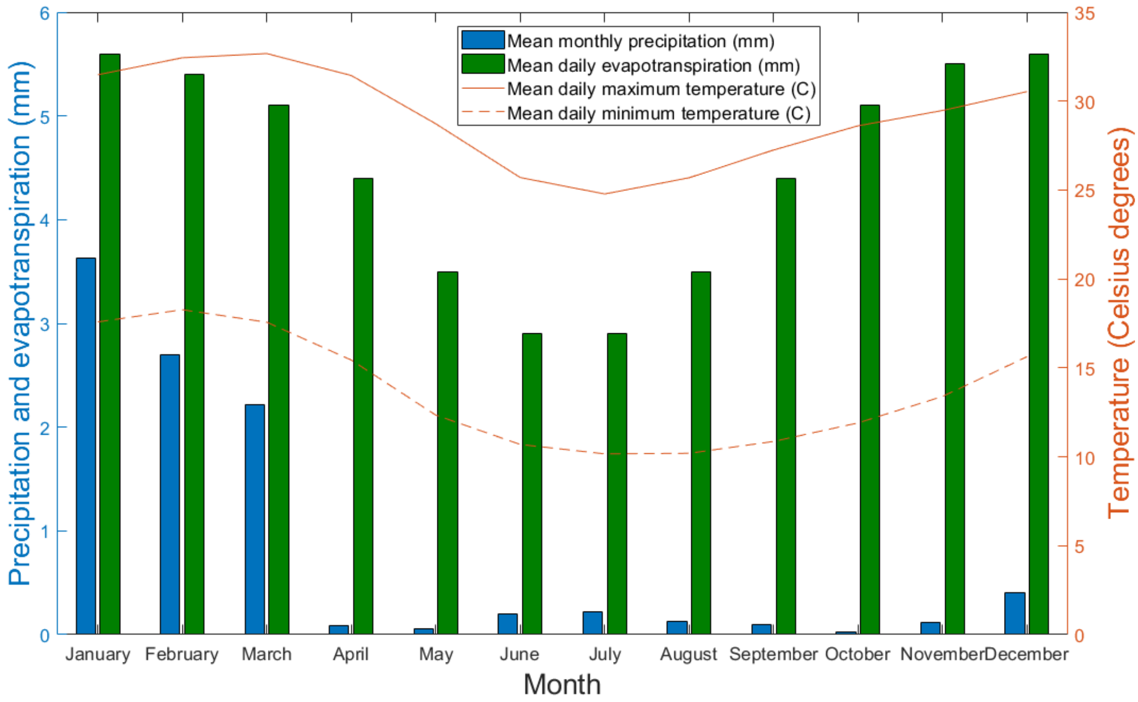


Figure 2-2. Mean monthly precipitation (mm) and mean daily reference evapotranspiration (ETo, mm)(left axis) and mean daily maximum and minimum temperature in Celsius degrees (right axis) in the Ica Valley between 1965-2017. Source: SENHAMI San Camillo station.

The arid climate conditions (Figure 2-2) explain why agriculture has developed so successfully in the area and its high dependence on irrigation. The hydrological regime is characterised by three significant periods (Oré, 2005): from September to December, the surface water comes from Choclococha system; from January to April, the superficial water comes from upstream rainfall or the melting of the glaciers; the rest of the year, the river is dry. Historically, groundwater, which is available throughout the year, was used as complementary resource to surface water, which was the most important and transferred and distributed through channels to the fields. However, there has been a reduction in water resources due to not only to the over-exploitation of the aquifer but also due to a reduction in superficial water because of a reduction in glacier mass (Peña, Sánchez and Pari, 2010).

2.2 Historical analysis of agricultural expansion

In order to understand the current water-related challenges and conflicts in the Ica Valley, it is necessary to first evaluate the trends in agricultural expansion and how this has evolved historically. A temporal analysis was carried out to assess changes in area, types of production system (small and large-scale farms) and agro-export trade and determine the implications on groundwater abstractions.

A spatial analysis was carried out to evaluate the dynamic changes in agricultural expansion since many of the new areas of cultivation have been on land that was previously natural vegetation. Data was obtained from Landsat satellite imagery (Zegarra, 2019), for four separate years (1990, 2003, 2010, 2017) with a spatial resolution of 30m; two main land uses were considered: small-scale and large-scale farms.

The historical series of agricultural production in the Ica Department (Ministerio de Agricultura y Riego, 2019) were studied between 1970 and 2017, distinguishing twelve main crop types in the Ica Valley: olives, alfalfa, cotton, asparagus, maize, mandarin, bean, avocado, potato, pecan, tangelo, and grapes. These crops were used for the WF calculations. The agricultural export trade for the period 1994-2017 in the Ica Valley (SUNAT, RADA and ADEX, 2019) was also analysed.

Finally, temporal trends in the Ica-Villacuri aquifer abstractions were evaluated. Although it has been shown that they are connected, previous studies have assessed each aquifer separately (ANA, 2012, 2017; Tahal Consulting Engineers, 1969).

2.3 Surface and groundwater footprint calculations

The methodology proposed by Hoekstra et al. (2011) was used in order to estimate the water footprint. For agricultural purposes in arid regions, only the blue WF is calculated, split into surface and groundwater components. The WF was determined in relative terms (volume per unit of product) for each crop individually and in absolute terms (volume) for each crop within a geographically delineated area.

The blue WF of a crop in relative terms (m^3/ton) was calculated as the accumulated of daily evapotranspiration from surface or groundwater (ET_{blue}, mm) over the length of the crop growing period in days (lgp), from planting to harvest divided by crop yield (Y, ton/ha) (Equation 2-1). ET_{blue} was divided according to the source of irrigation water into surface and groundwater. This WF was calculated for the period 1966-2017 corresponding to data available for crop yields and climate for that period.

$$WF_{crop,source}\,(\frac{m^3}{ton}) = \frac{10 * \sum_{d=1}^{lgp} ET_{blue,crop,source}\;(\frac{m^3}{ha})}{Y_{crop}(\frac{ha}{ton})} \tag{2-1}$$

The volumetric WF of a crop (m^3) was calculated as the crop water use multiplied by cropped area (Equation 2-2). This WF is used later for the water sustainability and water scarcity assessment.

$$WF_{crop,source}\,(m^3) = 10 * \sum_{d=1}^{lgp} ET_{blue,crop,source}\,\left(\frac{m^3}{ha}\right) * Area_{crop}\,(ha) \tag{2-2}$$

For irrigated agriculture, the blue evapotranspiration (ET_{blue}) is assessed as the minimum between the applied irrigation (AI, mm) and the consumptive part of the applied irrigation (CPAI, mm) (Equation 2-3). This distinction between both irrigation concepts is important where percolation could be significant (Perry, 2011).

$$ET_{blue}\,(mm) = \min(\,AI, CPAI) \tag{2-3}$$

AI was obtained from the WaSim modelling as the amount of irrigation applied to the crop. CPAI (Equation 2-3) was calculated as the difference between the actual crop water use (ET_a, mm) and effective precipitation (P_{eff}, mm) and takes place when P_{eff} has lower values than ET_a. ET_a was modelled with WaSim whereas effective rainfall was calculated as the part of the total amount of rainfall that is potentially available for meeting crop water use (Dastane, 1978).

$$CPAI\ (mm) = \max\ (0, \sum_{d=1}^{lgp} ET_a - \sum_{d=1}^{lgp} P_{eff}) \quad \textbf{(2-4)}$$

Therefore, in order to calculate the WF, it is necessary to know the crop yield, actual evapotranspiration, effective precipitation, and applied irrigation. Crop yield values were taken from historical data for the Ica Department for 1965-2017 (Ministerio de Agricultura y Riego, 2019); the remaining variables were estimated using a soil water balance, explained in detail in section 2.4.

Finally, to distinguish the WF between surface and groundwater, it was also necessary to define what proportion of each crop is irrigated from surface or groundwater. This was carried out using the ENA (Encuesta nacional agropecuaria) survey (INEI, 2017b), which provides data on crop production (area), method of irrigation, source of water used for irrigation, planting and harvesting dates, and if the owner is a small or large-scale farm. It was assumed that the proportions of surface and groundwater use were constant over the period 1965-2017.

2.4 Data parametrisation for the soil water balance modelling

The WaSim model considers precipitation and reference evapotranspiration (ET_o) as inputs; and actual evapotranspiration and drainage from the root zone as outputs (Hess, Harrison and Counsell, 2000). Table 2-1 summarises the parameters required to run WaSim; Appendix A includes the parameter values used for each crop.

Climatic data were available for the period 1965-2017 from San Camillo station, located within the Ica Valley. There were some missing values in the time series, monthly average data were used for gap filing. Reference evapotranspiration was calculated in the WaSim-ET program (Hess, 2000) based on the Penman-Monteith method.

Table 2-1. Input data and parameters required by WaSim

Data	Parameters	Source
Climate	Precipitation and reference evapotranspiration	(SENAMHI, 2015) San Camillo station (latitude: 14°4'23.91''; longitude: 75°42'39.63''; altitude: 407 m.a.s.l.)
Soil	Drainage coefficient, curve number, water content fractions (saturation, field capacity and permanent wilting point)	(Batjes, 2005; Hess, Harrison and Counsell, 2000; USDA, 1986, 2009)
Crop	Crop cover development dates: Planting, harvest, emergence, 20% cover, full cover, maturity and maximum root. Roots: Planting depth and maximum root depth. Cover: Maximum cover (%), crop coefficient and mulch cover (%). Transpirations: P-fraction and yield response.	(Allen et al., 1998; Doorenbos, Kassam and Van Der Wal, 1979; FAO, 2006)

Crop cover development dates were estimated depending on crop typology. If the crop was an annual, then the planting and harvesting dates were taken from the ENA survey (INEI, 2017b), with other developmental dates interpolated from FAO (2006). If the crop was permanent, only the harvest date was known; the remaining developmental dates were also interpolated from FAO (2006) considering a growing period of 365 days.

The irrigation schedule was estimated taking into account the irrigation method. Surface irrigation typically applies larger irrigation depths on a less frequent interval, while drip irrigation applies smaller irrigation depths but on a more frequent interval. For drip irrigation, the schedule was designed as daily irrigation back to field capacity. For surface irrigation, the schedule was defined as an application every 15 days of an amount proportional to the mean crop evapotranspiration (ET_o, mm) and the crop coefficient (Kc). It was a gross approximation based on the mean daily evapotranspiration (Figure 2-2) for each month.

The WaSim model was parameterised and then run for all 52 years, 12 crop types and 1 soil texture to derive values for ET_a, P_{eff} and the applied irrigation for calculating the ET_{blue} and potential recharge and runoff for calculating the renewable surface and groundwater, respectively.

2.5 Water scarcity and sustainability indicators

Water scarcity is evaluated by the water stress index (WS), which is defined as the ratio of the volumetric water footprint to the water availability (Equation 2-5). (Boulay et al., 2018; Hoekstra et al., 2012; Rezaei Kalvani et al., 2019). Groundwater availability was calculated as the amount of groundwater which is in good or medium condition minus the annual amount used for urban water supply; these values were obtained from Peña-Laureano, Sánchez-Díaz and Pari-Pinto (2010). Surface water availability was approximated as the monthly flow in the River Ica (ANA, 2017) minus an environmental flow, which was defined as 20% (Gjessing et al., 2011). In this way, the order of priority was given firstly to urban water supply, then the environment, and finally irrigated agriculture.

$$WS = \frac{Volumetric\ WF\ (m^3)}{Water\ availability\ (m^3)} \quad \textbf{(2-5)}$$

The WS indicator is ranked (Rezaei Kalvani et al., 2019) to show different degrees of scarcity (Table 2-2).

Table 2-2. Baseline score for assessment of water stress index

Range	Water stress level
WS<0.1	Low water stress
0.1<WS<0.5	Moderate water stress
0.5<WS<0.9	Severe water stress
WS>0.9	Extreme water

The sustainability of the water use by irrigated agriculture can be measured using the adapted ‘water debt repayment time’ indicator (WD) (Tuninetti, Tamea and Dalin, 2019); this provides a physical quantification of the time required to replenish the water resources used for crop production. It is calculated by dividing the volumetric WF into the water renewability (WR) produced by the crop, and splitting between surface and groundwater (Equation 2-6). In order to avoid hidden upstream dependency, the generated runoff and recharge values are considered without accounting for the water resources generated elsewhere. Therefore, the WR index is produced locally by each crop and takes into account both precipitation and irrigation. It has been defined as adapted WD indicator owing to the concept of renewability varies from the original (Tuninetti, Tamea and Dalin, 2019), which considered the runoff and recharge produced by the precipitation, but did not consider recharge from irrigation.

$$WD_{blue,source}\,(year) = \frac{Volumetric\ WF\ (m^3)}{(WR_{\ irrigation} + WR_{\ precipitation})(\frac{m^3}{year * ha})\ * Area(ha)} \quad \textbf{(2-6)}$$

Using individual years as a metric allows a better understanding of how long it takes for the hydrological cycle to renew the water used for irrigation. When the numerator is lower or equal to the denominator, then the resource is used sustainably. In contrast, if the numerator is higher than the denominator, this means that water resources are used by irrigated crops faster than the rate of renewal, and therefore, agricultural production is locally unsustainable. This unsustainability can lead to a depletion of local water resources or can indicate the reliance on water resource generated else-where.

2.6 Future plausible scenarios

Future plausible scenarios were developed to analyse not only the historical and current water-related challenges linked to irrigated agriculture but also to assess likely future changes. Two different scenarios were defined assuming the agricultural area will grow as it has been doing in the past, i.e., large-scale farms increase at an annual rate of 850 ha (according to the Section 2.1). Therefore, by 2030, it is expected that the large-scale farms will account for 17248 ha. The two scenarios are differentiated by the land they occupy:

- Scenario 1: Large-scale farm expansion is on bare soil. By 2030, a total 11050 ha will be converted from bare soil to large-scale farms.

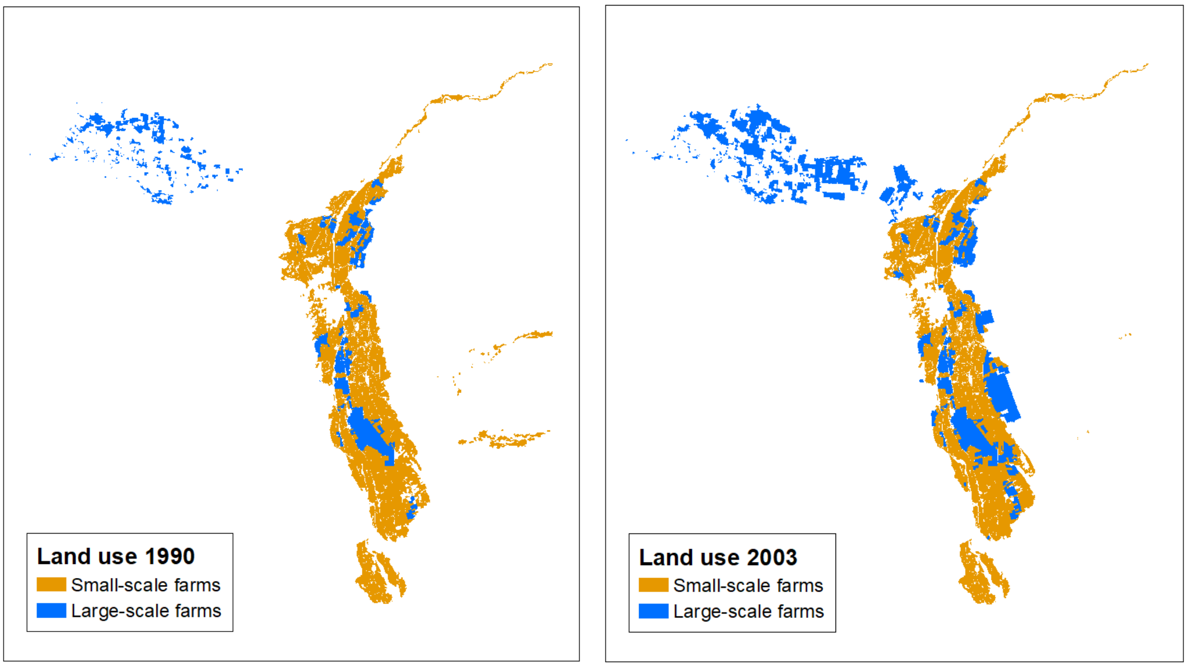
- Scenario 2: Large-scale farm expansion is at the expense of small-scale farms, which will be reduce from 14838 ha in 2017 to 3788 ha in 2030.

3 RESULTS

3.1 Historical agricultural expansion

The agricultural area for small-scale farming has remained almost constant over the period studied (Figure 3-1). However, large-scale farms have increased in area by 400% since 1990 with 7819 ha up to 30781 ha in 2017. In absolute terms, the area converted to irrigated land between 1990 to 2017 for agricultural purposes is 21700 ha (top panel Figure 3-2).

The satellite images (Figure 3-1) clearly show two differentiated areas, the Ica area (central and south of the valley), which is predominantly small-scale farms, and the Villacuri area (northwest), where large-scale farms have expanded their agricultural production.



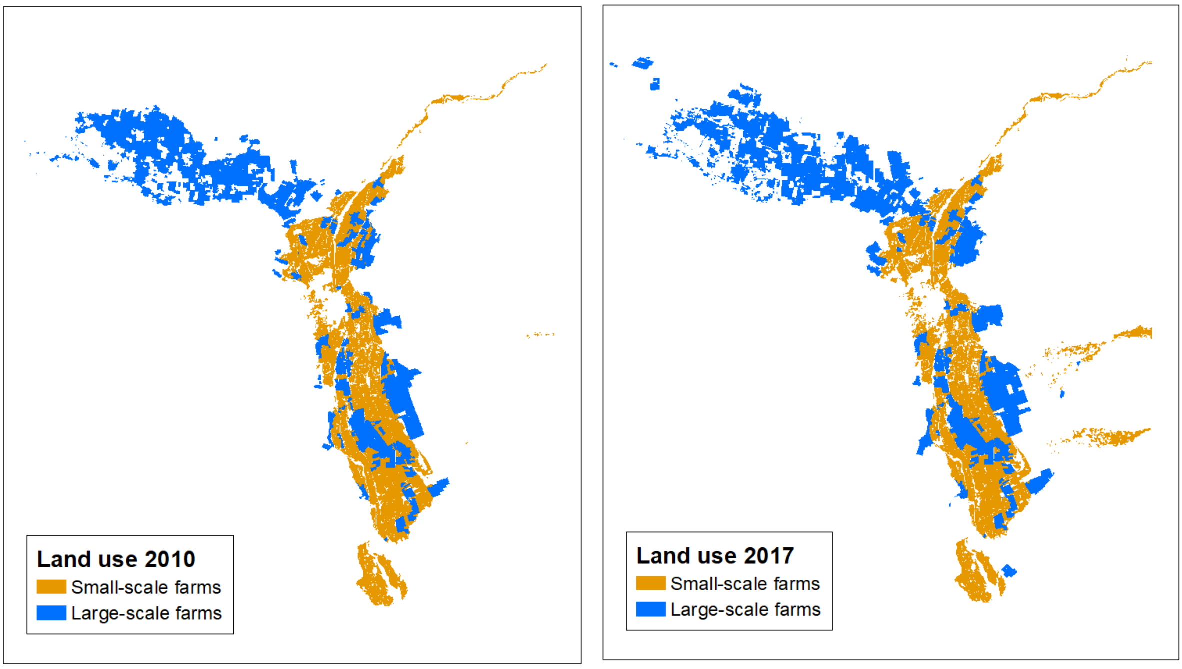


Figure 3-1. Spatial distribution of small and large-scale farms from satellite images based on (Zegarra, 2019) for four years (1990, 2003, 2010 and 2017).

Total crop production for the main 12 irrigated crops in the Ica Department was constant from the 1970s to the 1990s and after the 2000s it grew exponentially (middle panel in Figure 3-2). However, this trend was not followed by all crops. Some crops, such as potatoes, have maintained a constant production over the years. Other crops, such as asparagus, grapes and maize have all increased in production. Finally, the only crop that has decreased its production is cotton, from $76x10^3$ ton in 1970 to 15 ton in 2017. The agro-export trade (lower panel in Figure 3-2) shows a similar pattern to agricultural production, with export trade growing exponentially after 2005.

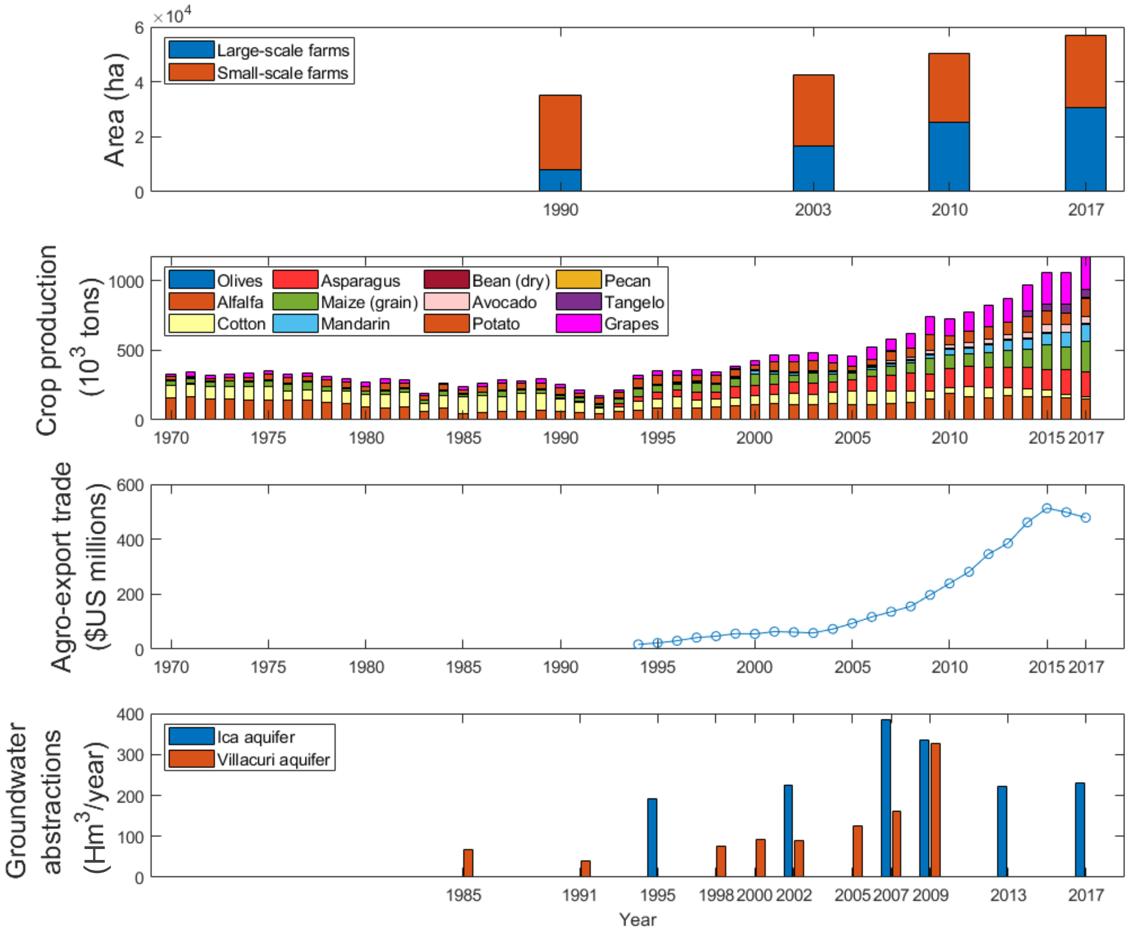


Figure 3-2. Historical data of (from top to bottom) agricultural area in the Ica Valley (ha), crop production in the Ica department (thousands tons), agro-export trade from the Ica Valley (US$ millions) and groundwater abstractions of Ica-Villacuri aquifer (Hm^3/years)

The historical trend in groundwater abstractions for the Ica-Villacuri aquifer as a whole have increased. The Villacuri aquifer exploitation has followed an exponential growth, whereas there is not such a clear trend for the Ica aquifer. From 1991 to 2009, the Villacuri aquifer's abstractions have increased by more than 300%. Nevertheless, the Ica aquifer's abstraction peaked in 2007 at almost 400 Hm^3/year but since then has declined to 231 Hm^3/year in 2017.

3.2 Analysis of existing crops in the Ica Valley

The twelve crops included in this study account for 87% of the total agricultural area and 91% of crop production in the Ica Valley. In particular, grapes, maize and asparagus, which are the three crops with the largest areas, cover half the agricultural area and account for 60% of production. Four of the crops are annual (maize, cotton, potato and bean) and the rest are permanent. Some crops are only grown by small-scale farmers, large-scale farms or both. The irrigation method can be surface or drip and can be from surface or groundwater (Table 3-1).

Table 3-1. Main crops in the Ica Valley, the percentage of the total agricultural area they occupy, the type of farm where they are produced, the irrigation method used and the source of the irrigation water for 2017.

Crop	%Area of total agricultural area		Type of farm	Irrigation via water source	Irrigation method
Grapes	21.9	42%	Small-scale	Surface water	Surface
		58%	Large-scale	Groundwater	Drip
Maize	14.6	94%	Small-scale	Surface water	Surface
		6%	Large-scale	Surface water	Surface
Asparagus	13.6	93%	Small-scale	Groundwater	Drip
		7%	Large-scale	Groundwater	Drip
Avocado	8.5	34%	Small-scale	Surface water	Surface
		66%	Large-scale	Groundwater	Drip
Cotton	6.0		Small-scale	Surface water	Surface
Potato	5.6		Small-scale	Surface water	Surface
Pecan	4.7		Small-scale	Surface water	Surface
Bean	3.6		Small-scale	Surface water	Surface
Olives	2.4		Large-scale	Groundwater	Drip
Mandarin	2.1		Large-scale	Groundwater	Drip
Alfalfa	1.9		Small-scale	Surface water	Surface
Tangelo	1.8		Large-scale	Groundwater	Drip

Grapes, maize, asparagus and avocado are produced by both farmer types, and only grapes and avocado, depending on the type of farms, use different sources of water for irrigation and method of irrigation application.

On the one hand, in all small-scale farms, except asparagus, use surface water source and surface irrigation method. On the other hand, in all large-scale farms, except maize, use groundwater source and drip irrigation method (INEI, 2017b).

3.3 Historical blue water footprint

The ET_{blue} and the blue WF (m^3/ton) for the 12 crops studied (Table 3-1) between 1965-2017 and split between surface and groundwater source were calculated and represented as box and whisker plot where red marks is the median, the edges of the box represents the 25^{th} and 75^{th} percentiles and the upper and low whiskers display the 9^{th} and 90^{th} percentiles (Figure 3-3). The shape of the box and whiskers shows that the ET_{blue} has less temporal variability than the blue WF in relative terms.

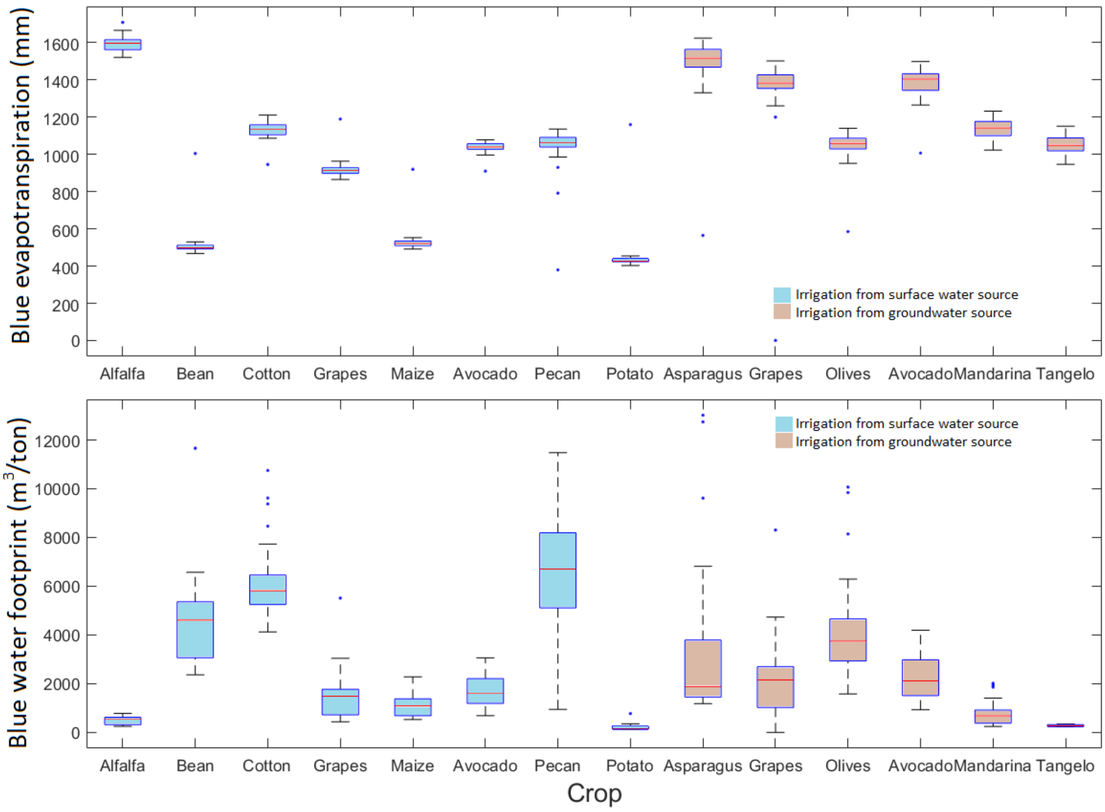


Figure 3-3. Blue crop water use (m^3/ha) and blue water footprint (m^3/ton), distinguishing between surface and groundwater, for the 12 crops studied in the Ica Valley between 1965-2017.

Amongst crops irrigated from surface water, those with higher values of ET_{blue} are alfalfa, cotton and pecan. Moreover, three out of the four annual crops (maize, potato and bean) show the lowest values of ET_{blue}. Amongst crops irrigated via groundwater, asparagus, avocado and grapes show the highest values of CWU_{blue}. Finally, analysing the two crops that are grown using both surface and groundwater, which are grapes and avocado, both show higher values of CWU_{blue} being irrigated via groundwater (drip irrigation) than via surface water (surface irrigation).

Considering the yields and the ET_{blue} of each crop over the period 1966-2017 the surface and groundwater WF were obtained. It is important to highlight that the same value of yield for surface and groundwater irrigation has been considered for grapes and avocado. Some crops such as alfalfa or potato have minimum variability in WF compared to other crops such as pecan, bean or asparagus. It is noteworthy that tangelo has minimum variability as there are only three values for yield (period 2014-2017). Moreover, the crops that show higher mean values of WF are pecan and cotton, followed by bean and olives. Overall, the mean surface WF (2775 m^3/ton) is higher than the mean groundwater WF (2110 m^3/ton).

3.4 Current volumetric water footprint

The total volumetric WF in 2017 was estimated to be 221Hm^3, accounting 60% for groundwater and 40% from surface water. Taken into account both sources of water, grapes (29%) have the highest values for WF followed by asparagus (23%), avocado (12%), maize (9%) and cotton (8%) (Figure 3-4).

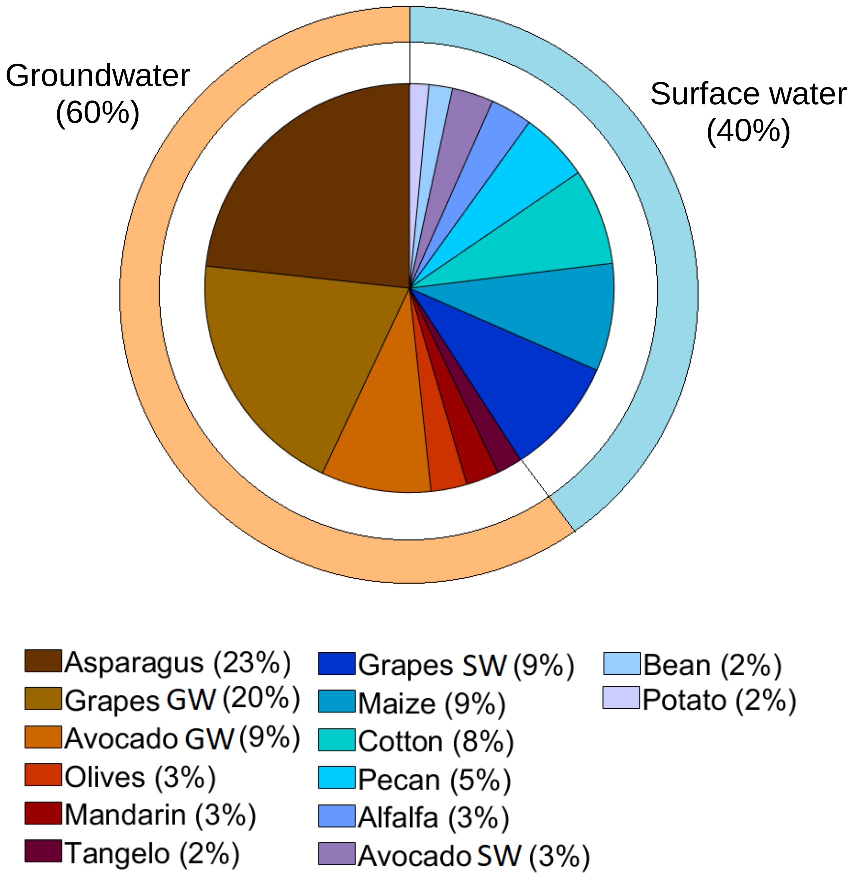


Figure 3-4. Allocation of volumetric blue water footprint for the year 2017, distinguishing between surface and groundwater.

Groundwater is available through the whole year, but surface water is not, so it is important the monthly consumptive surface water is considered.

3.5 Current water stress and water debt indicators

Water scarcity was assessed using the water stress index, which is calculated for both surface and groundwater. The annual groundwater availability is 770 Hm^3. However, as surface water availability depends on the season, it was assessed on a monthly basis (Figure 3-5). The results showed 17% of water stress for groundwater, and for surface water, a minimum of 0.4% for the wet period (from September to April) and a maximum of 5.3% for the dry period (From May to August), with an annual mean of 2% (figure 3-5). Those values show a low surface water stress level and moderate groundwater stress level.

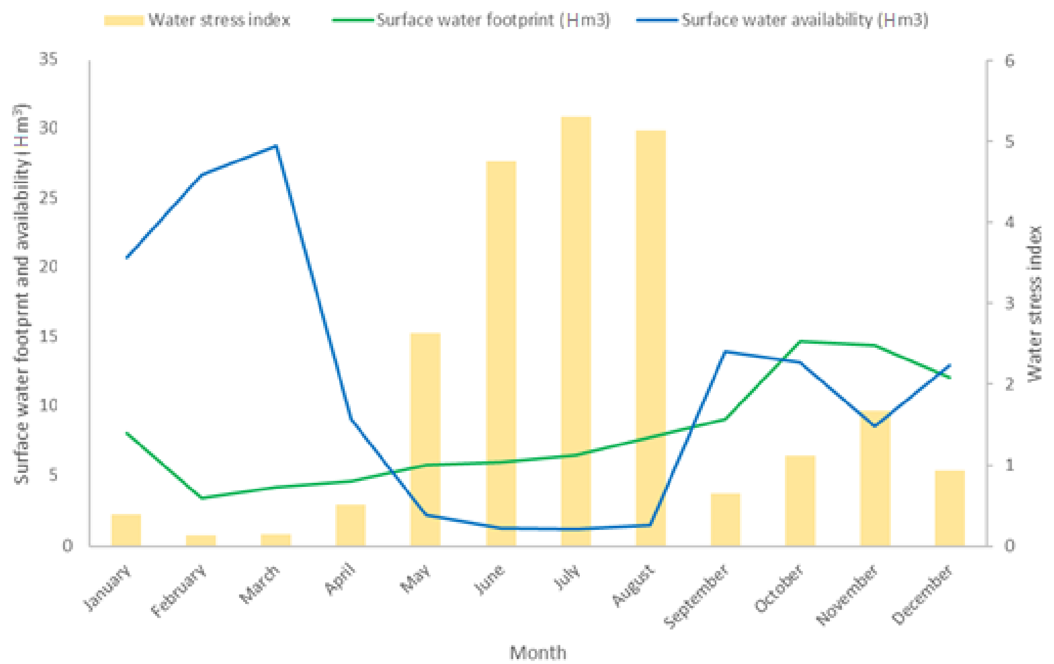


Figure 3-5. Monthly surface water footprint, monthly surface water availability and monthly water stress for 2017.

The water sustainability was assessed by the water debt repayment time, which shows that 8.4 years are required to replenish water used locally in the Ica Valley; this confirms that locally the current approach for abstraction for irrigated agriculture are unsustainable. The water renewability only occurs in terms of groundwater recharge from surface irrigation as there is no runoff or recharge from drip irrigation.

3.6 Water scarcity and sustainability for future plausible scenarios

Table 3-2 gathers the comparison between the current scenario, the future scenario considering the increase of agricultural area (large-scale farms) on bare soil and the future scenario where the increase of large-scale farms is done as a replacement of small-scale farms.

Scenario 1 implies a large increase in the groundwater WF, whereas only a slight increase in surface WF, as only one crop (maize) is grown in large scale farms and is irrigated via surface water. This scenario will intensify groundwater stress and unsustainability.

Scenario 2 implies a significant reduction in surface WF as well as recharge. This reduction in recharge will mean a higher level of unsustainability, as 30 years will be necessary to renew the water used for irrigated agriculture in one year.

Table 3-2. Values of water footprint, recharge, water stress and water debt for the year 2017, and the two proposed scenarios for the year 2030.

Scenario	Water footprint (Hm^3)		Recharge (Hm^3)	Water stress	Water debt
Current	WF_{total}= 220	$WF_{surface}$ = 131	26	2%	8.4 years
		WF_{ground} = 90	0	17%	
1	WF_{total}= 371	$WF_{surface}$ = 92	35	4%	10 years
		WF_{ground} = 279	0	36%	
2	WF_{total}= 269	$WF_{surface}$ = 26	9	1%	30 years
		WF_{ground} = 244	0	31%	

The limit between both scenarios will be when all small-scale farms have been replaced and then any remaining bare ground is converted to agro-export production. This could happen by year 18i.e., by 2034.

4 DISCUSSION

4.1 Historical changes in agriculture led to an agro-export boom

The results from this study show a clear and direct relationship between the agro-export boom and a rise in agricultural production and irrigated area. This agricultural expansion has caused an increase in groundwater abstraction, mainly from the Villacuri aquifer, due to large-scale farms being located far from the River Ica and relying entirely on groundwater resources.

In 1990 the area of small-scale farms was 3.5 times the area of large-scale farms, and in 2017, the area of large-scale farms has grown to the extent that they were 1.2 times the area of small-scale farms. In 2017 Peru was the second exporter country of asparagus, and Ica Department accounted for the 45% of national production (Moore, 2017) and was the third exporter country of grapes (Andina, 2017). It can be concluded that agricultural sector in the Ica Valley has aimed at agro-export. In fact, 26 out of the 50 main exporter companies in Peru are currently established in Ica (Rendón-Schineir, 2009).

With the agro-export boom, the agricultural frontier has expanded in last decades due to investments in irrigation infrastructure and pumping for groundwater abstractions. Consequently, agriculture is no longer limited to areas next to the river but also occupies arid zones (Damonte and Boelens, 2019). In the Ica Valley, the water abstractions of the Villacuri aquifer grow along with the increase of large-scale farms in the area above the aquifer. Both agro-export and the population growth has been intimated associated with trends of concentration in both land ownership and water access (Burneo, 2011; Damonte and Boelens, 2019).

Socio-political circumstances also contribute to the reasons behind the several peaks and troughs observed in the production historical trends and the overall agro-export boom. Ica Valley was already one the biggest producers of cotton in Peru in 1970 (Rendón-Schineir, 2009) due to new irrigation infrastructures, such as Choclococha Project in 1959, agricultural modernisation, and national legislation, which was beneficial for agro-export companies. Then, during the 1970s and 1980s, there wasn't agricultural expansion as the trend analysis showed. This was a consequence of the agrarian reform and the General Law of Water, which triggered the breakdown of relationships between the government and large-scale farmers (Philip, 2013).

Since the 1990s, it is observed an uninterrupted macroeconomic growth (De-Silva, 2011) of traditional commodities, such as cotton, and non-traditional products, such as asparagus, grapes, avocados and citrus. The reason of this progress is a neoliberal reform which fostered the formation of export companies boosting the export trade from the Andean regions and appealing external capital. Expansion in high value crops in the Ica Valley has been driven by the globalisation process and free-trade agreements which have opened international markets (Rendón-Schineir, 2009). Despite the agricultural growth, there are two main valleys observed in the historical trend: at the beginning of the 1990s and between 1999 and 2002, caused by a severe drought and El Niño (Oré, 2005), respectively.

4.2 An evaluation of the water footprint for a growing food demand

During the boom of the agro-export in the Ica Valley, appropriation of water resources has been characterised by an increase of water resources driven by a promotion of high value crops along with an inclusion of irrigation technologies.

Analysing the WF of crop production in a geographical area can help to visualise the hidden water use of crops, to understand the global impacts of water resources use and to quantify the trade on freshwater (Hoekstra et al., 2011). In the Ica Valley the two main crops that are grown for export purposes, asparagus and grapes, account for 52% of the total WF, with 43% of groundwater and 9% of surface water. These results signify that the use of freshwater in irrigated agriculture in the Ica Valley is spatially disconnected from its consumption (Hoekstra et al., 2011). Moreover, one of the most important contributions of this study is the differentiation between surface and groundwater footprint. The groundwater WF is 50% higher than the surface WF. Groundwater is mainly used by large-scale farms whose production is aimed at export. Thus, a greater portion of the water used from the Ica-Villacuri aquifer will be consumed abroad.

The WF (m^3/ton) obtained in this study can be compared with those obtained at national (MINAGRI, 2015) or global level (Mekonnen and Hoekstra, 2011). Peru is considered to be located in one of the areas that shows the highest values of WF worldwide (Mekonnen and Hoekstra, 2011). In the same way, the Ica Valley along with the northern and southern coastal areas within Peru, shows large values of blue WF (MINAGRI, 2015). Although different study periods and different soil water balance models were used in each study, the values can be comparable and the WF in the Ica Valley is slightly higher than the national mean.

The difference of temporal variability between ET_{blue} (mm) and WF (m^3/ton) over the study period 1966-2017, is due to an enhancement of yield values over the years. Along with the agro-export boom, the level of modernisation used in large-scale farms improved (Oré, 2005). In fact, there is a clear difference in the modernisation level in the Ica Valley between small-scale farms, which use surface irrigation system and large-scale farms that use drip irrigation system. Small-scale farmers use surface water for irrigation as they cannot afford to drill new wells or to deepen them when they are dried up (Wahlin, 2018). Besides large-scale farms have the advantage to have access to irrigation water the whole year and therefore, higher rates of productions. It has been proved by other studies, that an increase of yield through a more precision irrigation, such as drip irrigation systems, can reduce the WF (Chukalla, Krol and Hoekstra, 2015).

However, despite drip irrigation is potentially more efficient in terms of water application and can result in higher yields and better crop quality, it has been widely reported that it might lead to increased water consumption and reduced recharge (Jiménez-Martínez et al., 2009; Kendy et al., 2004; Rodríguez-Díaz et al., 2011). On the one hand, while favouring water conservation, drip irrigation also increases water consumption due to increased evapotranspiration (Han, Xu and Yang, 2017; Pulido-Velazquez et al., 2015). This, along with the assumption done by the WaSim model, are the reason behind the fact that crops irrigated via groundwater (using drip irrigation) show higher values of ET_{blue} than crops irrigated via surface water (using surface irrigation system). Moreover, a shift from surface irrigation to drip irrigation can lead to higher consumptive use owing to a shift of crop patterns to more water demanding crops and/or increase of agricultural area (Rodríguez-Díaz et al., 2011). This is called the rebound effect or Jevons paradox and it represents the unintended side-effects of increasing irrigation efficiency (Dumont, Mayor and López-Gunn, 2013).

On the other hand, drip irrigation system provides less recharge than surface irrigation system (Jiménez-Martínez et al., 2009; Kendy et al., 2004). According to the assumptions done by WaSim model (Hess, Harrison and Counsell, 2000), if soil water content is not higher than field capacity, there is no drainage from one compartment of soil to the other. Therefore, the selection of drip irrigation until field capacity in the soil, which is the one used in this study, does not generate recharge. This assumed drip irrigation schedule considers optimal irrigation conditions with no drainage losses which may differ in reality, and thus, deep percolation may exist (Ayars et al., 2001). This fact will have significant consequences for the water renewability in the Ica Valley and in turn the sustainability indicator.

4.3 Water scarcity and sustainability assessment

4.3.1 Optimal water management could reduce water scarcity and a higher recharge could reduce the level of unsustainability

The water scarcity for surface and groundwater were assessed using the water stress index. The groundwater stress is 8.5 higher than the mean surface water stress. Moreover, it is noteworthy to highlight that the surface water stress was analysed at a monthly time step. From January to April there is an excess of surface water that is not used either for agricultural nor environmental purposes. This would mean that, from a water management point of view, a better understanding of this temporal variability of water availability could reduce the water stress index. This water surplus could be stored and used for irrigation during the dry period. Other option is that large-scale farms could use that water surplus instead of groundwater during the wet period. Nevertheless, further studies would be required as the water footprint does not consider the irrigation efficiency and therefore, it does not represent the total amount of water withdrawn. Decision makers should optimise water use by an improvement of temporality in water management to meet water needs and increased water availability.

Water sustainability in irrigated croplands was assessed using the adapted water debt indicator. In arid environments, as the Ica Valley, considering the water renewability produced exclusively by precipitation and without including irrigation, as the original indicator (Tuninetti, Tamea and Dalin, 2019) would dismiss a great part of the renewability generated by the irrigated agriculture. Results showed that the water debt repayment time is 8 years for the year 2017, and therefore water used for crop production in the Ica Valley is dependent on water resources created upstream in the River Ica catchment and as a result locally unsustainable. Agriculture in the Ica Valley is highly dependent on upstream water resources as since 1959, the Choclococha system transfers surface water from a wetter Amazon basin to the River Ica basin. Furthermore, as the main recharge to the aquifer comes from the River Ica, it depends indirectly on water generated upstream. Thus, the scale of the study does not enable to study that dependency between the areas that generate the water resources and the areas where they are consumed. Moreover, results show that the agricultural sector in the Ica Valley is locally unsustainable as the only water renewability is caused by the recharge of crops irrigated via surface water as there is no recharge from drip irrigation. Perhaps it would be convenient to analyse the effect of different irrigation management practices on groundwater recharge. If local water renewability increases, the water debt repayment time could be reduced. This strategy could be accomplished by creating areas for artificial groundwater recharge or by shifting from drip irrigation to surface irrigation under designed irrigation schedules that optimises the relationship between crop water needs (ET_{blue}) and recharge.

In addition, considering the results obtained for future plausible scenarios, the level of unsustainability and water stress will increase considerably, especially that of groundwater. In those calculations, a decrease in water availability was not considered. However, because of climate change (Peña, Sánchez and Pari, 2010) and over-exploitation, the available surface and groundwater are expected to decline, and therefore, the water stress level will be worse than the one obtained in this study. Thus, there is a need to take action on water and agriculture management.

4.3.2 Implications for water policy

This assessment shows the necessity to take action against the overuse of water resources, mainly the groundwater, as the water use rate is quite higher than the local water renewability.

The future plausible scenarios are planned for the year 2030, the year in which it is expected to meet the sustainable development goals (SDGs). If no measure is applied the current assessment of the cropland production in the Ica Valley will be exacerbated. The groundwater overexploitation has greater implications for the population in the area as the urban supply relies totally on the Ica-Villacuri aquifer. If the agricultural expansion carries on at the same rate as it has been doing in the past decades, the agriculture will be the main responsible for not achieving the SDGs, in particular, the sixth SDG which aims to ensure accessibility and sustainable management of water and sanitation (United Nations, 2019). There are strong interactions between the SDG6 and other SGDs, such as, no poverty (SDG1), zero hunger (SDG2) and affordable and clean energy (SDG7). If there is no access to clean water and sanitation, the poverty cycle can be exacerbated in the Ica Valley negatively impacting the SDG1. If there is not enough quantity or quality of water, population in the Ica Department can have restricted access to safe drinking water for securing food and nutrition, as well as agriculture can be at risk as it relies on irrigation, which can affect the SDG2. Moreover, the way of management of water resource can impact on reaching an affordable and clean energy (SDG7). Thus, a failure on reaching the SDG6 in the Ica Valley can have devastating impacts the attainment of other SDGs (Mainali et al., 2018; Pradhan et al., 2017) and also the realisation of human rights such as right to food and to health (Wahlin, 2018).

A wise environmental water management is recognised as a key mechanism to fulfil the goals set in the Paris Agreement (SIWI, 2017). In order to decrease the groundwater abstraction, since 1970 there have been eleven bans of drilling new wells except for urban supply or water abstractions limitations. Despite these measures, the groundwater depletion has increased due to weak governance. Currently, there is a project which instead of decreasing groundwater abstractions, aims to increase the recharge using the surplus of surface water during the wet period (Escolero-Fuentes, 2017). However, owing to the high level of unsustainability and water scarcity and considering the homogeneous agricultural growth, this measure could be insufficient to reverse the current situation. Therefore, additional measures are required to decrease the water use.

Apart from reducing the current water consumption, it is also needed to increase water availability climate change may reduce the glacier mass where part of the surface water in the River Ica comes from (Peña, Sánchez and Pari, 2010). Moreover, the increasing demand of groundwater has limited the access to water to the also increasing local communities (Wahlin, 2018) water demand has increased agro-export boom has led to an increase of urban population, putting and adding pressure to the access of water resources in the Ica city (Oré, 2005).

Moreover, due to Peru and in particular the Ica Valley, are principal exporters of fruits and vegetables to other countries, such as United States, Spain, the Netherlands and the United Kingdom (Ministerio de Agricultura y Riego, 2019), the local water scarcity and sustainability could affect the supply chain of those products (Hess and Sutcliffe, 2018). Thus, food security from importer countries are also at risk.

5 CONCLUSIONS

This thesis has studied the agro-export boom in the Ica Valley due to agricultural expansion in the last few decades. Since the 1990s, the production, the export and the water abstractions have increased as a consequence of the politico-social circumstances. However, this exponential growth could be limited to the scarcity of water resources. This model of irrigated agriculture has led to an unsustainable use of water resources and moderate groundwater scarcity level. In 2017, groundwater footprint was 1.5 times higher than the surface water footprint and at least 50% of the water footprint in the Ica Valley is embedded in commodities products that are exported. Therefore, local water scarcity could affect the supply chain of fruits and vegetables to other countries.

Irrigated agriculture in the Ica Valley has detrimental effects on water resources, mainly for groundwater as results show moderate water stress level. In addition, cropland production is locally unsustainable and dependent on water resources created upstream, as 8 years are required to replenish the water resources consumed in one year. There is a need for optimising water resources management by increasing water availability and water renewability if it is intended to continue with the current model of agriculture. Otherwise, urban water supply and the countries which rely extensively on imports of fruits and vegetables from Peru will be increasingly negatively affected.

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APPENDICES

Appendix A Parameters for the soil water balance model

A.1 Soil parameters

The soil parameters required by WaSim are the water content, the curve number and the drainage coefficient (Table 1).

Table_Apx 1. Soil parameters values for WaSim

Water content	Saturation	0.453
	Field capacity	0.245
	Permanent wilting point	0.095
Runoff parameter	Curve number	78
Recharge parameter	Drainage coefficient	0.37

A.2 Crop parameters

The parameters required by WaSim model can be found in the Table 2. Planting date refers to the number of the day within a year of 365 days. The rest of the dates are referred as days after planting.

Twelve crops were studied. It is noteworthy that alfalfa was divided in 7 in order to fulfil the whole year.

Table_Apx 2. Crop parameters values for WaSim

Name	PlantingDate	Harvest Date	Emergence Date	Cover 20% Date	Full Cover Date	Maturity Date	Max Root Date	Planting Depth	Max Root Depth	Crop Coefficient	Yield response	pFraction
Grapes	61	365	1	30	65	265	1	0.05	1.5	85	0.85	0.35
Maize	244	140	12	25	40	45	40	0.05	1.35	120	1.25	0.55
Asparagus	15	365	1	90	120	320	15	0.04	1.5	95	1	0.45
Avocado	122	365	1	50	102	277	1	0.05	0.75	85	1	0.7
Cotton	91	305	30	61	183	244	183	0.05	1.35	120	0.85	0.65
Potato	105	140	15	30	65	115	65	0.05	0.5	115	1.1	0.35
Pecan	136	365	1	20	22	302	1	0.05	2.05	110	1	0.5
Bean	91	167	13	26	70	131	70	0.05	0.75	115	1.15	0.45
Olives	76	365	1	20	137	228	1	0.05	1.45	65	1	0.65
Mandarin	1	365	1	60	150	270	1	0.05	1.35	70	1.2	0.5

Alfalfa1	1	76	1	11	41	66	41	0.13	3	120	1.1	0.6
Alfalfa2	77	47	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Name	PlantingDate	Harvest Date	Emergence Date	Cover 20% Date	Full Cover Date	Maturity Date	Max Root Date	Planting Depth	Max Root Depth	Crop Coefficient	Yield response	pFraction
Alfalfa3	125	47	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Alfalfa4	173	47	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Alfalfa5	221	47	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Alfalfa6	268	47	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Alfalfa7	316	48	1	5	15	35	1	0.01	1.5	95	1.1	0.55
Tangelo	1	365	1	60	150	270	1	0.05	1.35	65	1.2	0.5