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Energized water: Evolution of water-energy nexus in the Spanish irrigated agriculture, 1950-2017

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Abstract

This study describes the evolution of the Spanish irrigated sector and focuses on water abstraction, water consumption, and energy use in the period 1950-2017. The analysis shows evidence of the basins reaching closure state and the impact on energy use from irrigation supply. The response in the context of an increasing water demand with a limited supply has been investment in water-saving and conservation technologies (WSCT) with the transformation of furrow-irrigated areas into those of drip and sprinkler, resulting in an increase in irrigation efficiency. The effect of this policy implies an increase in energy use by a factor of six in the period while the irrigated area triples and its water use doubles in the same period. Water abstraction reaches its peak in the year 2004 and decreases slightly as a consequence of subsidies to WSCT. The impact on energy consumption in pumping and treatment illustrates the water-energy nexus in Spain's agriculture and the change in the water policy paradigm from supply augmentation towards demand management.

Keywords

Water-energy nexus, Irrigation, Spain, Water accounting, Basin closure, Irrigation Efficiency, Non-conventional water sources

Highlights

- Evolution of water-energy nexus in Spanish irrigation illustrates the closure of the main basins and implementation of water conservation and non-conventional water sources
- Since 2005, water abstraction has been reduced due to modernization measures that result in increased energy consumption
- Water accounting at basin or aquifer level must be improved to closely control and measure water abstraction, water consumption, and energy
- The evolution of Spanish irrigation shows the effect of a mature water economy and the growing dependence on energy consumption

1. Introduction

Water scarcity constitutes a major concern for both developed and developing countries. Economic development generally involves an increase in water demand and its value since new uses (industry, urban settlements, and/or environmental concerns) or food production cause an increase in the use of the resource. In order to satisfy increased demand, the traditional response has been to increase supply. However, supply-side measures are limited when maximum capacity for water supply is reached and basins or aquifers are defined as 'closed' (Molle et al., 2010). Basin closure implies that any new demand can be satisfied only by reallocating water rights from existing users.

Investment in water-saving and conservation technologies (WSCT) has been a common response to the limited supply in closed basins, as has increasing energy consumption, since they are closely related (Zaman et al., 2012). As a consequence, management of water resources is expected to challenge not only freshwater resources but also energy-source constraints in many countries (Lee et al., 2018).

The water-energy-food (WEF) nexus has recently appeared as a research priority in academic and institutional settings (Zhang et al., 2019b). The framework initially appeared as a way to clarify the physical relationships between components, although more recently, certain specific methodologies have been proposed for the systemic analysis of the WEF nexus with the ultimate goal of reporting on nexus-related responses in terms of strategies, policy measures, planning, and institutional set-ups and/or interventions (Flammini, 2014). Albrecht et al. (2018) systematically reviewed the literature available on the WEF nexus and concluded that a significant share of approaches strive to improve resource-use efficiency between the WEF sectors, while Dargin et al. (2019) analysed how the water-energy-food nexus assessment tools vary in complexity and applications.

The WEF nexus involves various concepts (Huckleberry and Potts, 2019): (a) Water-energy, which refers to the consumption of energy to capture, store, transport, and purify water as well as for wastewater treatment; (b) Energy-water, which measures the use of water for either thermoelectric or hydropower energy production; (c) Energy-food, which measures the use of energy for machinery and equipment for crops and the energy for transport of intermediate and final products; and finally (d) Water-food, as the water needed to grow crops. Additionally, a fifth component involves the analysis of biomass for energy production.

This paper will focus exclusively on the first component, that is, the water-energy (WE) nexus as a subset of the WEF comprehensive framework. This is carried out by describing and estimating the water abstracted and consumed and the energy employed in supplying water for agriculture and by applying a methodology for the analysis of the evolution of irrigation water in Spain which can be considered representative of the adaptation to water scarcity of a semiarid (Mediterranean) developed country. Spain has addressed the issue of water scarcity with an extensive water reservoir network which makes the country the first in the ranking of per capita water reservoirs. Nevertheless, the increase in water storage has reached a limit and the majority of the basins have entered the closure stage (Berbel et al., 2013). As a response to the closure process, in the period 2002-2015, the country carried out an intense irrigation modernization process as an alternative to the limited availability of supply augmentation (Berbel et al., 2019). This investment in water-saving equipment and infrastructure has resulted in a growing consumption of energy by farmers (Fernández García et al., 2014; Rodríguez-Díaz et al., 2011).

This paper aims to illustrate the water-energy nexus in agriculture by conducting an in-depth analysis of a relevant case study with a long time series (1950-2017). The analysis of the evolution of Spanish irrigated agriculture will allow us to gain a perspective regarding not only the trajectories for water resources and the public and private response to scarcity of increasing energy consumption, but also of the effects of these responses.

In Spain, the policy of subsidies for water-saving infrastructure has played a major role and the responses regarding water-saving and increased energy consumption are well documented. This policy shows the water-energy nexus and highlights how water savings have been achieved at the expense of higher energy consumption, and therefore underlines the relevant need to integrate energy and water issues together in all decisions related to energy generation and water abstraction (Hardy and Garrido, 2012; Mayor Rodríguez, 2017; Villamayor-Tomas, 2017).

After describing the state of the art in the analysis of water-use efficiency and energy consumption in following section, we explain how the data gaps in the long-term have been addressed by detailing the methodology that is described in the third section. The results of the methodology that covers the complete series for the relevant water and energy variables are described in the fourth section, while the fifth section discusses the main findings, and the closing section proposes future avenues of research.

2. Current state of knowledge on water abstraction efficiency and energy consumption

The water-energy (WE) nexus is an emerging and significant topic in the research agenda worldwide. The role of institution and policies in the United States has been studied by Scott et al. (2011), who highlight the need for improved coordination between water and energy policy. Mercure et al. (2019) analysed the nexus in Brazil, and concluded that energy, water, and food are highly interrelated, and that policy for managing one probably affects the other two factors in often unpredictable ways; they recommend adjusting the scientific approach as an enabling condition for the strengthening of science-policy bridges.

Given the yield benefits from irrigated agriculture relative to rain-fed agriculture, in the future it is likely that society will demand more from irrigated agricultural production. Schwabe et al. (2017) analyse the trends over the past 35 years for the water-energy nexus in irrigated agriculture in the United States, and indicate there has been a significant increase in the adoption of irrigation systems of a more efficient nature and show how, between 1950 and the early 1980s, the acreage under irrigation nearly doubled. These changes, plus environmental restrictions and rising energy costs associated with electricity, could be the factors that motivate an overall decline in water application rates.

In the USA, the irrigation withdrawal declined by 9% from 2005 to 2010, which continued the trend from 2000 to 2005 (Barber, 2014). According Wang (2019), the reduction in water abstraction may be explained by increased technical efficiency supported by government subsidies. Wang (2019) indicates the USDA's Environmental Quality Incentives Program (EQIP) provided $4.2 billion in payments to landowners, and nearly a quarter of these payments were spent on support new irrigation systems in the years 1997 to 2010, and this author estimates the average technical irrigation efficiency as 0.73 for the year 2010; this efficiency is higher than global world average irrigation efficiency, which has been estimated at 65% (Postel et al., 1996). Huckleberry and Potts (2019) estimate the energy consumption for water pumping for the Lower Colorado River Basin to be approximately 88 kWh/hm^3.

In the Murray Darling Basin (Australia), the volume of water diversions (abstractions) for irrigation was in steady decline from 1997-98 to 2017 (with a small increase in the two years after the Millennium drought). This reduction is due both to direct buyouts of water rights by the Government and by a program of 3.5 billion Australian dollars for farmers' infrastructure subsidies (Grafton, 2019).

As mentioned earlier, in addition to USA, Australia, and Spain, several countries provide on-farm and off-farm subsidies to irrigators for water infrastructure (Perry et al., 2017) with the hypothesis that increasing irrigation efficiency will reduce water overexploitation and increase water availability for other uses including those of the environment. The debate of the unintended consequences of this policy, known as the 'rebound effect', will be discussed in the following sections with focus on the Spanish case.

3. Methodology and data

The basic material of this research is that of the official published data, although data gaps have been solved with certain estimations when the variable of interest is not directly registered. The objective is the analysis of the long-term evolution of Spanish irrigation water abstraction and of the consumption of energy for irrigation. The methodology is described in Figure 1 and shows the data source and the estimation process for the final variables.

Regarding terminology, the definitions proposed by the System of Environmental and Economic Accounting (SEEA) of the United Nations Statistics Division will be used, and specifically those of the SEEA-Water (United Nations, 2012) which define: (a) water abstraction (or withdrawal) is the amount of water that is removed from any source, either permanently or temporarily; (b) water consumed is assumed to be equal to evapotranspiration; and (c) return flow represents the water that returns to the basin after irrigation is performed. Regarding energy variables, the use and consumption of energy are taken as being synonymous.

Official data sources comprised statistical series from various bodies of Spanish government, which included the Ministry of Agriculture, Fisheries and Food (MAPA) for the total irrigated area, and for the area by irrigation method. MAPA also provides the number of engines related to irrigation pumps. The National Statistical Office (INE) provides water abstraction data in terms of irrigation method and source. Hydrological variables, such as water-table level (groundwater use) and efficiency of water distribution systems, was available from the Ministry of Environment (MITECO). The energy use has been estimated with engineering equations related to the volume of pumped water.

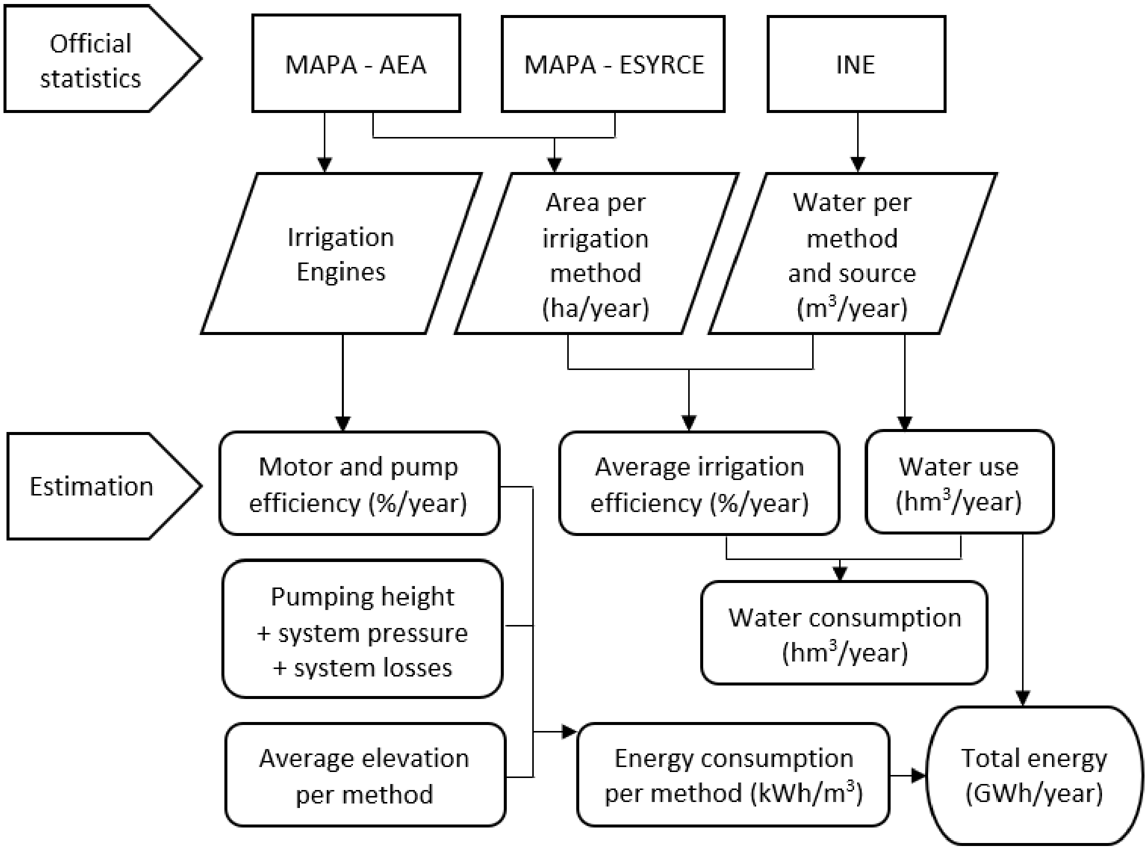

Figure 1. Methodological scheme.

A summary of the methodology, detailing the type of variables and the data source, is shown in Table 1.

Table 1. Data source, parameters, and variables (observed and estimated)

1. Observed variables	**Source**
a) Total irrigated area	MAPA (2019a): 1950-2017
b) Irrigated area by irrigation system	MAPA (2019a), MAPA (2019b): 1972-2017
c) Water abstraction[1] (m^3) by irrigation method	INE (2019a), INE (2019b): 1999-2016
d) Water use (hm^3) by source: surface water, groundwater, desalinated and reclaimed water	INE (2019b): 2000-2016
e) Number of diesel and electric engines for irrigation	MAPA (2019a): 1955-1996
f) Groundwater depth average	MITECO (2019b): 2000-2011
2. Parameters required for the model based on values found in the literature	**Source**
a) Irrigation efficiency by system: furrow 60%; sprinkler 80%; and drip 90	Berbel et al. (2018), Brouwer et al. (1989), Daccache et al. (2014), Zhang et al. (2019a)
b) Efficiencies of conveyance and distribution for irrigation were assumed: 90% and 90%	CHG (2012), Junta de Andalucía (2011)
3. Estimated variables	**Source**
a) Water consumption	Water abstraction multiplied by irrigation system efficiency
b) Return flow	Water abstraction minus water consumption
c) Energy consumption for pumping	Based on the equation [1] (Daccache et al., 2014)
d) Energy consumption required for desalinated water and reclaimed water	IDAE (2010), Lapuente (2012), López Unzu (2018), Martínez Álvarez et al. (2019)

(1) INE statistics refer to the water used, which is equivalent to water abstracted.

3.1. Irrigated area by irrigation method

The total irrigated area is probably the data known with the greatest reliability. The report “Survey on Areas, Yields and Crops” (ESYRCE in Spanish), published by MAPA, is the source for the years 2002-2017; while for the remaining years we use the Statistical Yearbook (AEA in Spanish), published by MAPA for the period 1950-2001. Data on irrigation systems by method (furrow, drip, and sprinkler) has been available since 1972 (MAPA-AEA). From 2002, a more detailed ESYRCE survey has been available.

The missing data per time period is shown in Table 2. A first analysis consisted of a preview of sequence charts. Missing values in the input data were subsequently replaced with imputed values, using a linear interpolation replacement method executed in time-series forecasting software from IBM® SPSS®. The following criteria were assumed: a) sprinkler irrigation was introduced in the late 1960s, whereby year 1967 is assumed as the initial year; and b) drip irrigation was introduced at the beginning of the 1980s, whereby year 1981 is assumed as the initial year.

Table 2. Missing data in the time series per period.

Method	Missing Data per time period	Missing values	(%)
Furrow	1967-1971, 1980-1988, 1990-1996, 2000-2001	23	34
Sprinkler	1967-1971, 2000-2001	7	10
Drip	1980-1988, 1990, 1992-1996, 2000-2001	17	25

The total irrigation area continuously grew in the period by approximately 1% annually with a smaller growth rate in the period 1998-2006 although growth rates returned to above 1% in 2007-2017. The lower growth rate in 1998-2006 may be due to the period of intense modernization where investment was largely directed inside the already existing irrigable areas[1]. It should be noted that drip irrigation at present occupies the largest share nationwide, amounting to 51% of the total irrigated land. Figure 2 shows the evolution of the irrigated area in terms of total area and irrigation methods.

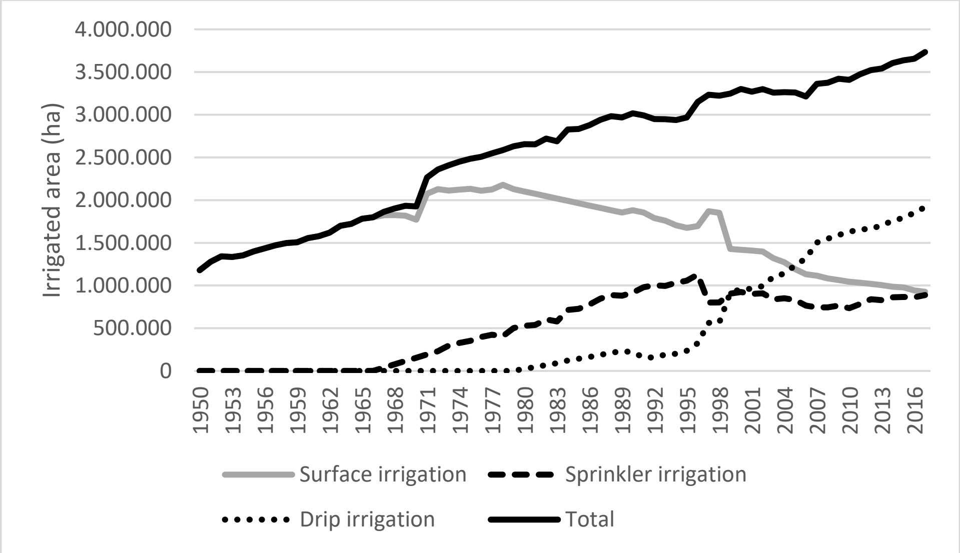

Figure 2. Irrigation area in Spain, 1950-2017. Source: Own elaboration based on data from MAPA.

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[1] Areas with water rights but not necessarily irrigated

3.2. Water abstraction and water consumption per irrigation method

Since 1999, the National Statistical Office (INE) has recorded the volume of water abstracted by different sectors of the economy. In the agricultural sector, the statistics include volume of annual water abstracted in terms of irrigation methods and resource origin. As shown in Figure 3, the annual water abstracted differs significantly in accordance with the method of irrigation.

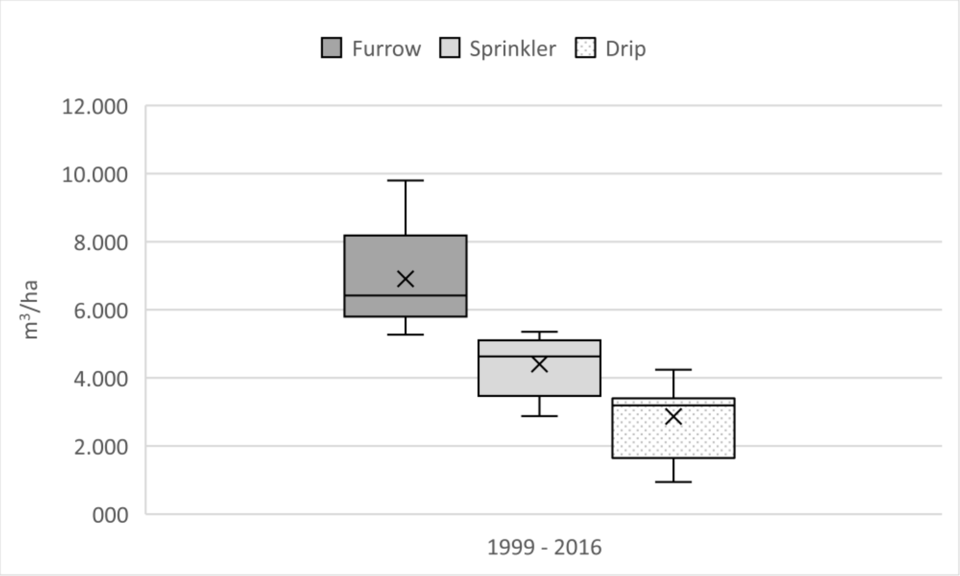

Figure 3. Water applied (m^3/ha) per irrigation method, 1999-2016. Source: Own elaboration based on data from INE.

In order to complete the gap in the data regarding water abstraction from 1950-1998, medians from the available years of 1999-2016 were used as the most robust measure of central tendency for a retrospective extrapolation. To this end, the median of annual water allocated per hectare (m^3/ha) in accordance with the irrigation method was multiplied by the irrigation area in accordance with the system for the estimation of the water abstracted by each system in the period 1950-1998.

The variable water abstracted per system is essential for the computation of the energy consumed by each irrigation method and is subsequently aggregated (see the following section).

The irrigation method determines the efficiency in the use of water, which we considered as the ratio of evapotranspiration (water consumed by the crops) with water abstraction. Although there are several estimates of the average application efficiency of each irrigation method, our approach considered indicative standard values of the same. These values are the same assumed in several irrigation water management literature (Berbel et al., 2018; Brouwer et al., 1989; Daccache et al., 2014; Zhang et al., 2019a). The application efficiencies that were used in this work are 60% for surface irrigation, 80% for sprinkler irrigation, and 90% for drip irrigation.

For conveyance and distribution efficiency values we relied on the irrigation and hydrological plans 2000s, considering as a representative sample of agricultural irrigation in the north and south of Spain the Guadalquivir and Duero river Basin. Considering the proportion of pipelines, covered canal, grounded canal, drained and ground ditches, in the south the conveyance and distribution efficiencies have a weighted average of 92% and 92% respectively (CHG, 2012; Junta de Andalucía, 2011). In the Duero river basin, conveyance and distribution efficiency approximate 94% and 88% respectively (CHD, 2019). In our analysis the efficiency of conveyance and distribution for irrigation were assumed at 90% and 90%, respectively, for surface water source and 100% for groundwater. By applying these efficiencies to the irrigated areas per system, the parameter of irrigation efficiency can be estimated.

The determination of real crop evapotranspiration presents a complex agronomic research task and no data is available at the regional or national scale, therefore the proposed approach constitutes a step in the direction of quantifying water abstraction and water consumption, whose importance is highlighted below. The estimated global system average efficiency for all irrigation of the national territory increases from 0.49 in 1950 to 0.69 in 2017 (including conveyance losses), while farm application efficiency increases from 0.60 in 1950 to 0.80 in 2017. Figure 4 shows the values of water abstraction, consumption, and returns, the latter having been measured as the difference thereof.

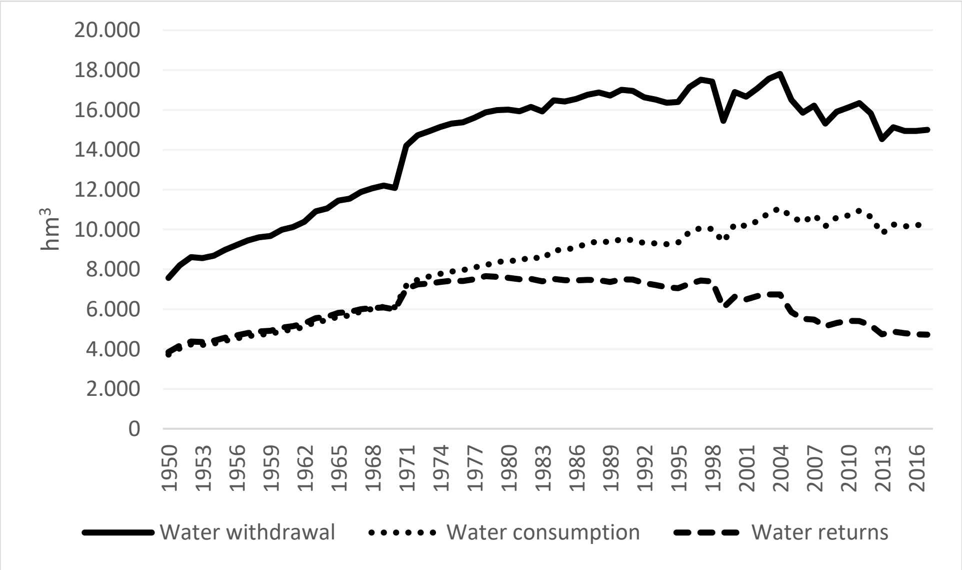

Figure 4. Volume of water abstracted, consumption, and return flows in Spain, 1950-2017.

Source: Own elaboration based on data from INE.

The volume of water abstracted has increased in parallel to the irrigated area (see Fig. 2) 1950-2004, reaching a maximum at 17,808 hm^3. The water consumed is estimated by multiplying water abstractions by conveyance and distribution efficiency. Irrigation returns are defined as the differences between abstraction and consumption; Figure 4 shows that return flows decrease from 1980 although the return flows decrease faster from 2004 according to our estimation.

3.3. Energy consumption

The energy consumed in irrigation depends directly on the volume pumped, the irrigation system, the efficiency of the pump, and the motor's source of fuel. As shown in Figure 1, the proposed methodology for the estimation of energy consumption of Spanish irrigation is related to the volume of water used by each system, either from official data or from our own estimation for those years prior to the availability of the series. Equation [1] estimates energy use as a function of water abstracted (m^3) and total pressure head (TH), which is in turn estimated in equation [2].

$$Energy\ (kWh) = \frac{Volume\ (m^3) \cdot TH\ (m)}{367 \cdot \mu_{pump} \cdot \mu_{motor}} \qquad [1]$$

TH is the sum of: $Lift$ (depth to groundwater); and H_{min} which is the typical working pressure of the different systems (surface irrigation = 0, sprinkler = 3 bars, and drip = 1 bar). Additional pressure is normally added at the head of these systems to guarantee uniformity, pressure losses of around 20% are assumed from friction in the irrigation system.

$$\mathrm{TH}_{(m)} = Lift_{(m)} + H_{\min(m)} + f_{Losses(m)} \qquad [2]$$

An additional pumping energy (lift) was considered for water abstracted from groundwater when compared to direct abstraction from surface water sources. The pumping lift data were derived from the groundwater depth average from 2000-2011 (MITECO, 2019b) and weighted depending on the mix of abstraction sources (surface and groundwater) each year. The groundwater depth average was approximately 60 m; the global water table depth dataset (Fan et al., 2013) indicates for Spain a range essentially between 20-80 m below land surface.

Once the necessary pressure is determined, the energy consumed by the pumping systems is calculated with eq. [1], which is widely used in irrigation engineering (see Daccache et al., 2014). This equation relates the volume extracted (m^3) with the work pressure contributed height (m) and is divided by a factor that relates the water volume with energy (kWh) and two factors. These factors are the efficiency of the pump in converting the motor energy into hydrodynamic pressure with μ_{pump} = 0.8 regardless of the power source used, and the efficiency of the motor, taken as μ_{motor} = 0.4 for diesel engines, where there is a large loss of energy in the form of heat, and 0.9 for electric motors, which are more efficient. The number of pumps powered by electric power have been increasing progressively since the 1980s in Spain, and the evolution of electric vs. diesel pumps is also considered in the model.

Data for engines were available for years 1955-1996. We estimated the missing data by regression from period 1980-1996 to fit a trendline curve to compute forecasts giving 3% of cumulative increase for electric motors that showed a similar annual growth rate (≈ 3%), that increased the electricity use by farms.

Regarding the use of energy for furrow irrigation, some of the farms may not use any energy (pumping height =0) however, others use water from a lake, or a river and need a certain level of pumping. As a proxy for the energy required for transport of surface water to the field, we used 5 meters of pressure as energy required for all surface irrigation (conveyance and transport). In the case of sprinkler and drip irrigation systems at farm plot, there would be a need for additional pressure.

Data on annual water supply by alternative water sources (reclaimed and desalination) is available from Statistical Office (INE). During the period 2000-2017, reclaimed water was regularly around 1.48% of the total irrigation water supply. Desalinated water has been steadily growing from near zero in the year 2000 to 0.94% of water supply in 2017. Energy consumed by reclaimed water account for a stable share on average of 14% of the total energy consumption (2000-2017 period), while desalinated water has grown from almost zero (2000) to 22% of total energy in (2017). It should be noted the enormous impact of desalination and reclaimed water in the energy consumption of the irrigated sector as deduced from the abovementioned figures.

4. Results

The water-energy nexus trajectory for irrigation in Spain yields several interesting results, where the annual water abstraction and energy consumption is plotted for the series 1950-2017 (Fig. 5). On the left, Figure 5 all annual data are shown, whereas the right of the figure focuses on critical years, to show a clearer presentation of the evolution avoiding temporal fluctuations (e.g. droughts or very humid years). Also, the right of the figure is linked to Table 3 proposing some historical phases in the period under analysis. The curve becomes gradually more vertical as the water abstracted reaches the available volume (this event is called ‘basin closure’) and the increased area causes an increase in energy consumption (Fig 2).

The evolution of water abstractions and energy consumption can be categorized into different periods, which illustrate the changes in the contexts: a) transition from open basins (new demand can be satisfied with additional supply) to closed basins (new demand requires re-allocation from already existing uses); b) conversion from traditional (furrow, open channels) to pressurized and precision irrigation; and c) introduction of alternative supply sources in the form of desalination and wastewater reclamation. The combination of these three changes in context provides the explanation of the behaviour of the WE nexus in the period 1950-2017 (Fig. 5).

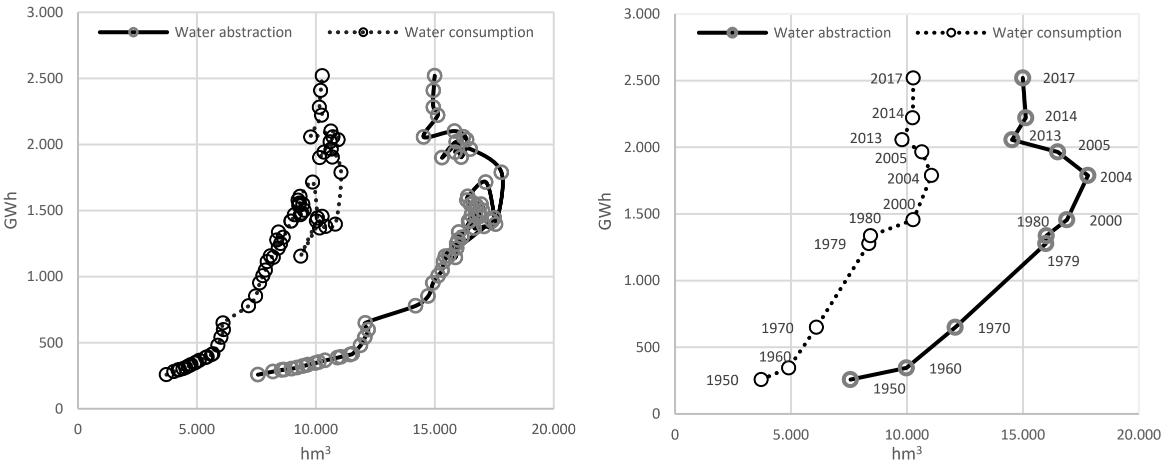

Figure 5. Evolution of water abstracted and consumed vs. energy used for irrigation in Spain.

The selected years on the right in Figure 5 and Table 3 indicate milestones in the series for water withdrawal with the estimated water consumption that follows a related trajectory. We propose four stages in the evolution of the water-energy nexus in Spanish irrigation as summarized in Table 3, illustrated for variables per volume, energy use and per area water use in Figure 6.

Table 3. Estimated water withdrawal, water consumption, irrigated area, and energy consumption in Spain in selected years.

Indicator	**Year**						**Annual growth (%)**			
	1950	**1960**	**1980**	**2004**	**2013**	**2017**	***1950-1979***	***1980-2004***	***2005-2013***	***2014-2017***
Irrigated area (10^3 ha)	1179	1555	2656	3264	3541	3734	*2.8%*	*0.9%*	*1.0%*	*1.2%*
Water abstraction (hm^3)	7568	9984	16016	17808	14535	14998	*2.6%*	*0.4%*	*-1.6%*	*-0.3%*
Water consumption (hm^3)	3721	4909	8436	11065	9794	10277	*2.8%*	*1.1%*	*-1.0%*	*0.1%*
Energy consumption (GWh)	258	345	1336	1788	2056	2520	*5.5%*	*0.5%*	*-1.4%*	*1.1%*
Per area water abstraction (m^3/ha)	6419	6419	6031	5456	4105	4017	*-0.2%*	*-0.4%*	*-2.6%*	*-1.5%*
Application Efficiency	0.60	0.60	0.64	0.76	0.79	0.80	*0.2%*	*0.7%*	*0.4%*	*0.3%*
Energy use kWh/m^3	0.03	0.03	0.08	0.10	0.14	0.17	*2.9%*	*0.8%*	*2.2%*	*4.5%*

Source: Own elaboration from various sources.

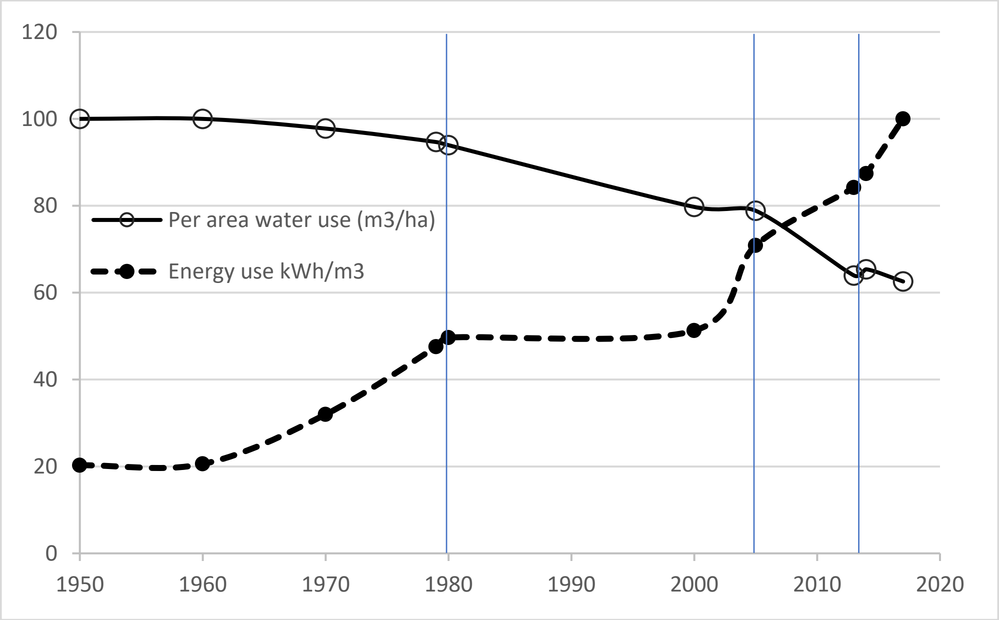

Figure 6. Evolution of per hectare water abstracted and per volume energy use in Spain.

The main indicators from Table 3 and Figure 6 can serve as a basis for the definition of four transforming stages of development in the WE nexus, and these are:

Area expansion (1950-1979): There is a strong positive correlation between the water abstraction and the irrigated area. The milestone that signals the end of the phase may be the transition of the Franco regime to democracy (1975-1978), the economic crisis during 1975-1982, and the existence of a severe long drought (1978-1984). The increase in the volume of water abstraction gradually forced a greater use of energy, although the slope is moderate, since in the 1970s, the adoption of sprinkle irrigation systems boosted the WE dependence. The water scarcity is not evident in this stage since the water allocation is stable and the area and abstracted volume follow parallel trends.

Closure (1980-2004): During the 1980s, Spain developed its agriculture with the opening of European markets and its adhesion to the European Community (in the year 1986). Drip irrigation was introduced at the beginning of the 1980s in Spain, thereby progressively increasing the energy dependency and opening the door to a new competitive horticulture and export-oriented fruticulture (mainly EU markets). The farmers responded to the extreme drought in 1992-1995 with an increase in the area irrigated. In this phase, water abstraction reached the maximum volume in the year 2004, which indicated the arrival of basin closure. The water abstraction and water consumption curves in Figure 5 gradually increase their slope into vertical lines, thereby illustrating a clear water-energy trade-off and basin closure.

Modernization (2005-2013): The milestone herein could be the drought of 2004-2008 and the Royal Decree 10/2005 which created the legal framework for subsidizing water-saving investments (‘modernization’) (Berbel et al., 2019). In this phase, there is a 16% reduction in water withdrawals, and water consumption stabilizes, while energy consumption and irrigated area continue to grow. There is a widespread implementation of volumetric pricing systems that forced farmers to move from the flat rate per hectare (generalized up to 2010) to a binomial system where the variable part, which is around 30% of the total water cost, is determined volumetrically. The rate of energy use during that period decreased due to the substitution of fuel pumps with electric pumps. Along with the rising cost of energy and the generalization of the binomial tariff, the modernizations imply a reduction in the entitlements of irrigators of 25% for the basins where scarcity is more extreme (in south and southeast Spain), and explain the reduction in volume abstracted as a direct result.

Present and outlook for the future (2014 onwards): The milestone for this stage may be the ending of modernization policy (subsidies to water-saving infrastructure) due to the economic crisis. During the previous phase, modernization transformed 1.7 million hectares, whereby the water saving was greater, and the remaining irrigated areas were either less productive or more expensive to transform. This period shows significant changes in almost all variables: a) water abstraction decreases slightly (-0.3%); b) water consumption increases slightly (+0.1%); c) per-area water application is reduced by -1.5% yearly; d) there is an abrupt increase in energy consumption per volume. Water abstraction per type of crop in 2016 was: herbaceous (56%), citrus and fruit trees (16%), vegetables (11%), olive grove and vineyard (8%), and other crops (9%). The drought in the Eastern basins reduced surface supply and stimulated the use of desalination and reclaimed wastewater for irrigation which explained the steep vertical growth of the last segment of the WE curve.

The short period of the last four years may be considered irrelevant, but, in our opinion, it initiates a new paradigm with high water efficiency and use of alternative water supply that should be monitored closely. The last stage has seen a significant increase in energy consumption for irrigation nationally and especially per unit (kWh/m^3), which can be explained by the use of alternative water sources in the form of desalinated and reclaimed water. Figure 7 shows the difference between the total energy consumption in Spanish irrigation including alternative water sources and the consumption calculated by only considering conventional water sources (surface and groundwater).

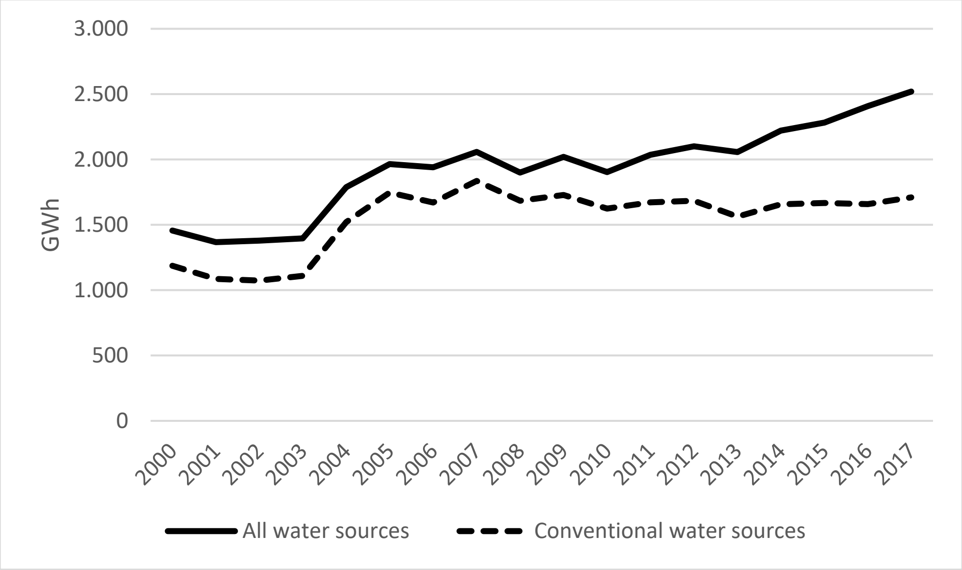

Figure 7. Evolution of the energy consumption in Spanish irrigation. Source: Own elaboration based on data from INE and IDAE.

The energy requirements are significantly higher for desalinated water in comparison to reclaimed water. Throughout 2014-2017, there is a trend showing an increase in the use of desalinated water, which explains the higher energy consumption at national level, although the use of desalinated water is concentrated in southeast Spain.

5. Discussion

Overall, the trend of Spanish irrigated agriculture in the period 1950-2017 shows an average annual growth of irrigated area of 1.72%, whereas water abstractions increase annually by 1.02%, and energy consumption increases by 3.40% per year. During this period, certain basins became fully allocated in the 1990s and the government responded by subsidizing investments into infrastructure and water-saving equipment during the early 2000s, with a fivefold increase in energy consumption per water abstraction between 1960 and 2017. The increase in the ratio of energy to water is due to the introduction of pressurized systems as a response to water scarcity and, in more recent years, due to the introduction of alternative supply sources. As expected, although water withdrawal has been reduced since its maximum in 2004, this reduction does not lead to savings in water consumption but does lead to its stabilization.

The reaching of the system boundary (or basin closure) in Spain has already been described for the case of the Guadalquivir basin (Berbel et al., 2013), and this underlines the increase in irrigated area accompanied with the introduction of water-saving technologies, and the increase in water costs. The economic consequences of this closure in terms of productivity of the resource (also in the case of the Guadalquivir) are shown in Expósito and Berbel

(2017), whereby productivity gains seem to have reached a ceiling due to technological innovations having reached the limits of their capacity in creating new value. The present work shows that a phenomenon such as that described for this basin is occurring on a national scale. Southern and Mediterranean irrigated agriculture accounts for 85% of groundwater, 88% of desalinated and reclaimed water, and 61% of surface water used in Spain, as well as 92% of the water used by drip irrigation systems, which currently represents more than 50% of the irrigated area (INE, 2019b; MAPA, 2019b). Also, the highest added value is in the southern and Mediterranean irrigation sector, so citations explaining the events in this area have relevance at national level.

Our methodology is relatively simple and supported by reliable data from official statistics: the irrigated area per method and the volumes used by the irrigation methods where some gaps in the time series have been completed with estimates that probably reflect reality. The efficiency estimates for the approximation of water consumed from water abstraction are based on typical values that are frequently found in the literature. All parameters have been selected as the most frequent according to the literature and they have been assumed constant for the whole period 1950-2017 (a simplifying assumption as some parameters may have improved such as pumping motor efficiency). We have performed some sensitivity analysis to the parameters assumed in the model (system efficiency, motors efficiency) such as that developed by Zhang et al. (2019a) and finally decided to avoid the presentation of the different results as the parameters that have been finally chosen are the most frequent values quoted in the literature. In our opinion, the model illustrates the evolution of water use, consumption and energy use in Spanish irrigated systems with a good degree of realism. Nevertheless, readers can access and use the original data and parameters in the ‘Supplementary material’ for free use.

Based on our estimation, as efficiency grows (from 0.49 in the 60s to 0.69 in 2017) and consequently, as water abstraction stabilizes in around 2004 (or are even reduced slightly from 2004 to 2017), the water consumption continues to grow and consequently return flows (fraction not consumed) are reduced. This has consequences for the management of watersheds, which have already been analysed elsewhere (Berbel et al., 2018).

Our model shows an increasing share of the evapotranspiration fraction and reduced return flows so that smaller abstraction volume does not reduce water consumption. Also, our estimation has not detected increased consumption after 2004 even as the irrigated area keeps growing. Therefore our model does not confirm the existence of the ‘rebound effect’ due to modernization (Gutiérrez-Martín and Gomez-Gomez, 2011; Perry et al., 2017). The increased irrigated area has been coupled with reduced water dose as water use per hectare (from 6419 to 4017, i.e. 38%) decreased. This reduction has been possible due to the combination of two techniques, by one hand, increase in water efficiency (reduced losses) and on the other hand, the growing importance of deficit irrigation. Deficit irrigation applies irrigation during crop sensitive growth stages periods, this results in plant stress and yields below technical maximum and increases water productivity. Deficit irrigation is generalized in some crops such as olive groves, vineyards or almond leading to some basins such as Guadalquivir to reach an average relative irrigation supply (RIS) of 0.60 (Berbel et al., 2011).

National information on the energy consumption by Spanish irrigation remains scarce. Hardy et al. (2012), from various secondary sources, estimated a value of 2469 GWh (year 2008) for the energy consumption required for the distribution and water abstraction in Spanish agriculture (including livestock). Our estimation for the energy consumption in irrigation nationwide in 2008 accounted for 1900 GWh. Another estimation of this parameter is provided by Corominas (2010), who based the value on several secondary sources and indicated that between 1950 and 2007 the consumption of energy for irrigation increased from 309 to 5866 GWh, which is much higher than our estimation, although the methodology is not explicit.

The gap with the data produced by Corominas (2010) is very significant, yet we have not been able to access neither the methodology nor, the materials used for the mentioned work. Our opinion is that there is some erroneous information in the report such as water use in the agricultural sector that according INE was 16,897 hm^3 for year 2000 while Corominas report 23,870 hm^3. We have contacted the author, but the material and methodology are not available currently so that we cannot find the source of these previous estimations.

The increase in energy consumption is an undesired effect of technical change, although it should be noted that a global analysis of the impact of the modernization policy is complex since, according to the work of Borrego-Marín and Berbel (2019), on the one hand CO_2 is emitted when pumping water, but on the other hand there are savings of greenhouse gases due to a lower use of fertilizers and the area of fruit trees that increase carbon capture, partially or totally compensating for (depending on each basin and each case) the increase in energy consumption.

When reviewing the contribution of the emission sources, crop management is responsible for 25% of $CO_{2\text{-eq}}$ emissions in Spanish agriculture with the remaining 75% due to livestock production; main emissions of rainfed and irrigated agriculture comes from synthetic fertilizers and soil management (FAOSTAT, 2019; MITECO, 2019a). On farm pumping for irrigation represents 23% of the on-farm energy use for crop production (Sloggett, 1992). The analysis of the emissions by water pumping and infrastructure isolated from land use changes and rest of inputs maybe misleading (Aguilera et al., 2015a, b) nevertheless, some authors have conducted this simplified analysis converting GWh to $CO_{2\text{-eq}}$.

In addition, the integration of unconventional water resources as a means of adaptation to face the risk of drought, is estimated to be more intense and frequent in the future due to climate change (Morote et al., 2019). In the United States, Schwabe et al. (2017) indicate that, as groundwater levels become more depleted, we can expect energy costs to rise, a quicker and wider adoption of highly efficient irrigation systems, and greater incentives to utilize surface water supplies. Furthermore, it has been discussed that extreme extraction of groundwater represents a serious threat to sustainable development (Yannopoulos et al., 2015).

Regarding increased use of energy, Mushtaq et al. (2013) analyse the climate-change impact of irrigation modernization in Australia, although the analysis was limited to financial effects and emissions of $CO_{2\text{-eq}}$ due to the change from previous open channels to pressurized networks and it fails to include the positive impact of increased $CO_{2\text{-eq}}$ storage in both soil and trees. This latest indicator was included by Borrego-Marín and Berbel (2019) in a cost-benefit analysis of modernization policy. In response to the increasing cost of energy, solar-powered systems have been implemented. Although the promotion of solar-based pumping for irrigation may present advantages for energy policies, it may also have potentially negative impacts on the environment caused by excessive resource abstraction (Closas and Rap, 2017).

There are examples of regional case analysis, such as that provided by Siddiqi and Anadon (2011), who describe the water-energy nexus in the Middle East and North Africa and quote that the consumption of electricity used for desalination in Arabian Gulf countries lies between 5% and 12%. In Israel, the adoption of seawater desalination technology remains the leading policy strategy to deal with the Israel water crisis, thus advancing the creation of a new water regime (Bismuth et al., 2016; Teschner et al., 2012). In California, for current conditions, the production cost and regulatory hurdles form the limiting factors of desalination. Nevertheless, emerging innovative technologies, such as the combination of the reduction of pre-treatment and efficient membrane technology, energy recovery systems, and efficient brine management, boost the likelihood of seeing California become a leader in desalination (Rocha, 2017).

Soto-García et al. (2013) analysed the energy consumption for crop irrigation in the southeast of Spain for period 2002–2011 and showed that desalinated brackish water is the highest energy consumption source. Desalination and wastewater strategies should be considered in water policies. However, due to the high costs of the water produced, it is not advisable to use these technologies as the only solution (Molina and Melgarejo, 2016). Correspondingly, there is an increasing need to find and incorporate methods for the energy requirements of irrigation pumps that do not depend on imported oil and electricity (Yannopoulos et al., 2015).

Finally, in Spain, the demand for alternative water sources for irrigation is concentrated along the Mediterranean coast, where water availability is restricted. As Martinez-Granados and Calatrava (2014) indicate, the over-exploitation of aquifers constitutes a major problem in southeast Spain, although in some areas, the availability of desalinated seawater resources is expanding. The trend of increased use of desalinated water has been shown in our analyses and therefore must be considered for the future planning and policy design of water and energy in Spain's irrigation.

According to the European Environmental Agency, total water abstraction in Europe has decreased by more than 20% over the last 15 years[2]. Unfortunately, the Agency report provides data on trends in terms of the amount of water abstraction for irrigation in Europe and use the land area subject to irrigation as a 'proxy'; however, as we can see in the case of Spain and also for USA 2000-2010, this assumption is obviously wrong and misleading (Wang, 2019).

We need to point out that we have not focused in any specific location as the analysis aims to be nationwide. Obviously, the different national polices and external events (EU accession) have been national country policies promoted at national level affecting the whole country, although with regional differences, but we believe that country level analysis reflect the global evolution and is a better indicator of the changes in the WEF nexus that focusing in a specific area. The application of the model at river basins level is a relevant issue but the available data at river basin level has a short time span (since 2005) and the number of variables is reduced to perform this long-term analysis at basin level.

6. Conclusions and policy implications

The present study is the first carried out nationwide for a long-term series (1950-2017) with a detailed analysis of the joint evolution of irrigation efficiency and irrigation energy consumption. The main results illustrate the closure of the main basins characterized by the reduction of supply-augmenting measures and the emphasis on water conservation equipment that increases the efficiency of water abstraction and reduces return flows. The change of paradigm from supply policy to demand management as defined by the intense modernization with a strong presence of public subsidies has resulted in increased energy use per unit of water and, more recently, in the introduction of alternative supply sources. Regarding the data quality and reliability, in our research, we have witnessed major improvement in data quality since 1999, including water abstraction statistics (related to the implementation of the Water Framework Directive), while data gaps from 1950-1998 have required from our expertise and estimation, Nevertheless, the most significant changes have occurred in the last 20 years (increases in basin closures, energy consumption, and water consumption).

The data used paints a coherent picture of the process and presents several relevant questions for the future of water management in water-scarce regions. It remains convenient, however, that analysis based on official statistical data is supplemented by data on actual

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[2] EEA, 2018. Water abstraction; https://www.eea.europa.eu/archived/archived-content-water-topic/water-resources/water-abstraction

evapotranspiration, return flows, and the status of water bodies. The estimation of water consumption could be complemented with remote sensing to measure or estimate evapotranspiration. In general, the use of water accounting at basin or aquifer level must be improved in order to more closely control and measure water abstraction, water consumption, and energy use, especially under growing uncertainty derived from climate-change impacts on water resources. Nevertheless, the analysis of currently existing European Union policies whose specific focus is on nexus thinking, reflects the fact that cross-sectorial effects, especially across all three nexus resources, have only recently been accounted for and predominantly, exist in the form of non-formalized statements of intent (Venghaus and Hake, 2018).

In our opinion, the WEF nexus should consider both the positive effects ($CO_{2\text{-eq}}$ capture) and negative effects ($CO_{2\text{-eq}}$ generation) of water-saving investment and alternative supply sources regarding climate-change mitigation and greenhouse gas emission. This, in our opinion, constitutes a critical point to be addressed in future research.

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