Evaluation of alternatives for flood irrigation and water usage in Spain under Mediterranean climate

I. García-Garizábal[a, c, *]

ikerggarizabal@gmail.com

J. Causapé[b]

D. Merchán[~~b~~, 1]

[a]Spanish National Institute for Agricultural and Food Research and Technology (INIA), Ctra de la Coruña, Km 7,5, 28040 Madrid, Spain

[b]Instituto Geológico y Minero de España (IGME), C/Manuel Lasala n° 44 9° B., 50006 Zaragoza, Spain

[c] Center of Alternative and Renewable Energy, Department of Renewable Energy Engineering, Federal University of Paraiba, Cx Postal 5115, 58051-900, João Pessoa, Paraíba, Brazil

*Corresponding author.

[1]~~-~~Independent researcher.

Abstract

Evaluation of water management has been progressively more necessary to determine the availability of water resources, especially in the Mediterranean environment where competition for these resources is maximum.

This work evaluates the irrigation management and evolution of hydric needs for the main crops implemented in the Ebro basin (Spain), through the monitoring of a pilot experimental basin between 1998 and 2012. This 15-year period comprehends changes in irrigation implemented by the Irrigation District as well as climate and agronomic variabilities of the region.

Changes in water management (implementation of an on-demand irrigation system with annual water allowances and payment per surface and consumption, in opposition to an irrigation system in shifts) and crops contributed to reduce irrigation by 40% and drainage by 72%. This occurred due to better adjustments between the water volumes applied and the hydric needs of the crops, achieving flood irrigation efficiencies of 80%. However, small negative trends were detected in the water deficit evolution of corn and sunflower, which should be addressed and improved.

Improvements in water management by farmers have enabled the increase of irrigation efficiency up to values found in pressurized irrigation systems, especially in initial stages of the irrigation campaigns. However, specific water deficit episodes were detected that should be remediated.

Keywords: Irrigation water management; Irrigation efficiency; Water balance; Water deficit; Ebro river basin

~~1.~~ 1 Introduction

Evaluation of water management in arid regions is becoming increasingly necessary to determine the availability of water resources, as competition for this resource is maximum and is predicted to increase during the XXI century. In fact, climate studies developed up to date predict a lower availability of water resources in the Mediterranean environment: decreases in precipitation and increases in temperatures (IPCC, 2007, 2008) will have strong consequences on the regional water balance.

In this sense, considering that the agricultural sector is the greatest consumer of water in the world (FAO, 2006), it is necessary to rethink and evaluate the use and management of water in this sector. The bottom line is to obtain adequate agrarian efficiencies without causing simultaneous negative impacts to the natural environment.

Therefore, although irrigation enables the increase and maintenance of agricultural productions (FAO, 2003), it is also the responsible for soil (Tanji and Kielen, 2002; Liu et al., 2012; García-Garizábal et al., 2014a; Gkiougkisa et al., 2015) and water degradation due to salts (Causapé et al., 2004b; Isidoro et al., 2006; Thayalakumaran et al., 2007; Duncan et al., 2008; Abrahao et al., 2011a~~, 2011b~~; García-Garizábal et al., 2014a) and other agrochemicals (Causapé et al., 2004b; Thayalakumaran et al., 2008; Abrahao et al., 2011b; Petrovic et al., 2011; García-Garizábal et al., 2012b, 2014b), being nitrate and phosphorus the main issues associated with the occurrence of anoxic zones and eutrophication of aquatic environments (Diaz, 2001; Scavia and Bricker, 2006; Wang, 2006).

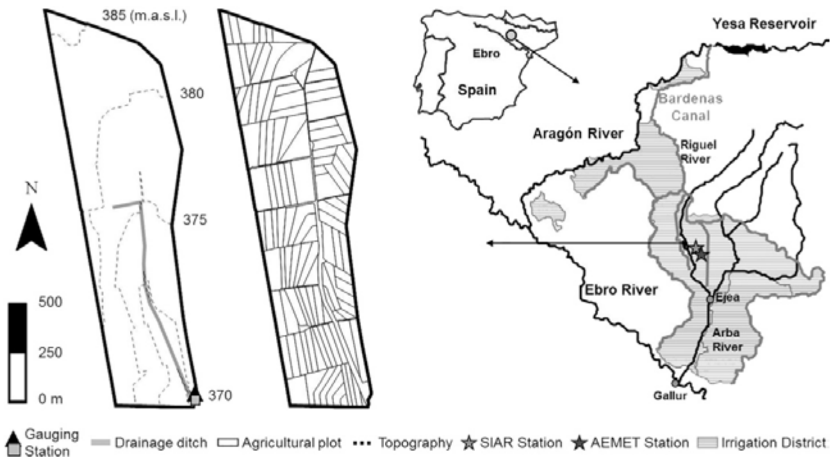
Up to now, studies on agricultural usage and contamination of soil and water have been carried out using lysimeters in small experimental plots (Roman et al., 1999; Caballero et al., 2001; Spalding et al., 2001; Isla and González, 2006; Feng et al., 2005; Gehl et al., 2005; Bustos et al., 2006; Li et al., 2007). More recently, monitoring of irrigation hydrological basins has been utilized (Tedeschi et al., 2001; Cavero et al., 2003; Causapé et al., 2004a; Isidoro et al., 2004; García-Garizábal and Causapé, 2010; Abrahao et al., 2011a; Barros et al., 2011; García-Garizábal et al., 2011), which is a methodology considered to be highly appropriate to evaluate water management at plot and irrigation district levels.

Nevertheless, although the work carried out in previous studies provided knowledge on water management in the agricultural sector, the studies approached a low temporal resolution. This hindered the drawing of adequate conclusions on irrigation management for agricultural districts, mainly due to the high annual climate variability that exists in the Mediterranean area.

The objective of the work herein presented is to evaluate water management in a pilot basin with traditional irrigation, with Mediterranean climate conditions in the Ebro valley, between1998–2012. This work extends the study period developed by García-Garizábal et al. (2011; 2001–2008) and better accommodates the climate and agronomic variabilities of the region.

~~2.~~2 Description of the study zone

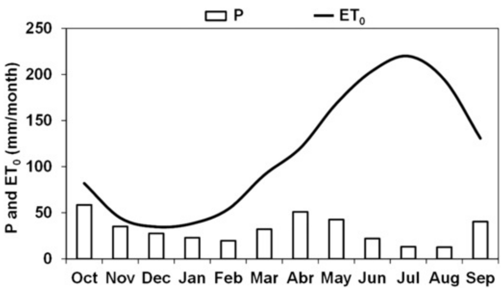
The study zone corresponds to the superficial hydrological basin D-XIX-6 at the Bardenas Irrigation District (BID, Fig. 1). The network of canals that surround D-XIX-6 acts as a surface water divider, limiting a 95 ha basin that is flood-irrigated.



~~Figure 1.~~Fig. 1 Location of the experimental basin D-XIX-6 within the Bardenas irrigation system and weather stations employed in the study.

alt-text: Fig. 1

Annual reference potential evapotranspiration by Penman-Monteith (ET_0) during 1998–2012 was 1382 mm with low inter-annual variability (3%). Associated with higher temperatures, 45% of ET_0 occurred in Summer (June–July–August), while only 9% of annual ET_0occurred in Winter (December–January–February; Fig. 2).



~~Figure 2.~~Fig. 2 Monthly average precipitation (P) and reference evapotranspiration (ET_0) values in the study zone, for the period 1998–2012.

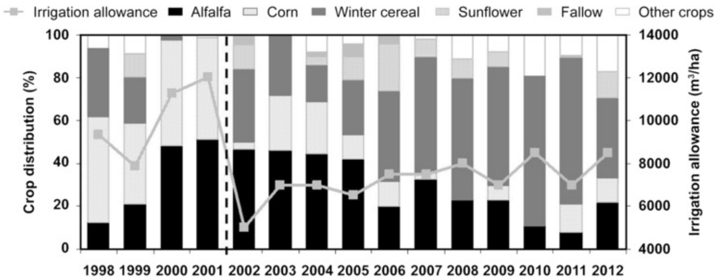
alt-text: Fig. 2

Precipitation reaches an average value of 374 mm and is the most irregular climate component, with a 30% inter-annual variability. In years with low precipitations, only 165 mm of rain was registered while rainy years reached values close to 600 mm, with maximums in Spring (March-–April-–May) and Autumn (September-–October-–November; Fig. 2).

Regarding the soil that constitutes the zone, two lithologic units can be distinguished (Lecina et al., 2005; García-Garizábal et al., 2011). The higher areas of the basin correspond to glacis levels where layers of gravel with loamy matrix (11-–43%) develop with average water retention capacity of 111 mm (Calcixerollic Xerochrept).

The topographically more depressed zones are developed on tertiary impermeable substrate, providing the soils with thin limestone and gypsum levels interbedded (4-–18%) as well as higher water retention capacity (158 mm; Typic Xerofluvent).

The main implemented crops were corn, alfalfa, winter cereal and sunflower, with annual distribution varying significantly during the study period (Fig. 3). While alfalfa and corn predominated in the period 1998-–2001, after 2002 the farmers opted for crops with lower hydric needs such as winter cereal and sunflower.



~~Figure 3.~~Fig. 3 Distribution (%) of main crops and annual irrigation allowance (m^3/ha) in basin D-XIX-6 during 1998-–2012. Data on irrigation allowance provided by BID.

alt-text: Fig. 3

In this sense, the 2006 change in the subsidy system of the Community Agricultural Policy (which allocated grants independently of production; Alvarez-Coque, 2006) motivated an extension of the surface destined to winter cereal.

The employed irrigation system is flood irrigation, which underwent changes during the study period. While between 1998 and 2001 (before changes) flood irrigation was applied in shifts (12-–14 day irrigation intervals), after 2002 (after changes) the BID implemented an on-demand irrigation system to improve water use. Annual water allowances and bynominal tariffs (payment per surface and consumption) were introduced and the farmer decided the date and irrigation dose to be applied.

~~3.~~3 Methodology

Evaluation of water use in the studied irrigated area during 1998-–2012 followed the adequate closure of annual water balances, which were accomplished by the Irrigation Land Environmental Evaluation Tool (*In Spanish*, EvaluadorMedioambiental de Regadíos-–EMR; Causapé, 2009).

~~3.1.~~3.1 Water balance

The methodology for water balances consists in quantifying the hydrological components (inputs, outputs, and storage) for a specific territory. After satisfactory closures are achieved (closure errors ± 10%), the components for each balance term can be considered to have been adequately measured and can be further employed to develop management analyses with indices based on these components (Causapé et al., 2004a~~, 2004b~~; Isidoro et al., 2004; Barros et al., 2011; Abrahao et al., 2011a~~, 2011b~~; García-Garizábal et al., 2012a~~, 2012b~~; Merchán et al., 2015).

As the irrigated area proposed by García-Garizábal et al. (2011) had already reached acceptable balance closure errors (-– 1 to 2%), the water balance carried out by EMR enabled the extrapolation of the balance to the remaining study years and evaluation of irrigation quality by indices. In this sense, the soil water balance equation was:

$$(I + P) - (ET_R + D) = AW$$

where the inputs (irrigation, I and precipitation, P) minus the outputs (evapotranspiration, ET_R and drainage, D) equals the variation of water in the soil (Available Water, AW).

Daily data on irrigation (I) were provided by BID, where the study was carried out. Regarding climate data, daily precipitation was obtained from the weather stations at El Bayo (from the Meteorology State Agency and Integrated Irrigation Advisory Service, SIAR

Network). Precipitation registries in the area started in 1998.

Annual pluviometry was classified based on the local reference series for the period 1971~~-~~–2000 (García-Garizábal et al., 2014c), according to i) Standardized Precipitation Index (SPI; McKee et al., 1993), which is considered to be the best climate indicator to identify dry-rainy periods (Keyantash and Dracup, 2002); and ii) Percent of Normal Precipitation (PNP), basic index for precipitation analysis that refers to the relationship between the accumulated precipitation throughout one year (P_{year}) and the annual average precipitation for a region in a given period ($P_{1971-2000}$):

$$\mathrm{PNP}\,(\%) = 100\cdot\left(\mathrm{P_{year}} - \mathrm{P_{1971-2000}}\right)/\mathrm{P_{1971-2000}}$$

Real evapotranspiration was calculated daily, through soil water balances from daily ET_0data and crop coefficients (Kc; García-Vera and Martínez-Cob, 2004) for the crops implemented in the zone, by calculation of potential evapotranspiration ($ET_C = ET_0 \cdot Kc$; Allen et al., 1998).

For the period 2005~~-~~–2012, daily ET_0 data were obtained from the SIAR station. Between 1998 and 2004, ET_0 was calculated following the correlation recommendations of Martínez-Cob and Tejero-Juste (2004) and CEDEX (2013), between daily ET_0 by the Hargreaves method and ET_0 by the Penman-Monteith method (Allen et al., 1998), since the period 2005~~-~~–2009 coincided for AEMET and SIAR stations.

Once daily data was obtained for I, P and ET_0 as well as water holding capacity for each agricultural plot, EMR developed daily water balances that corrected ET_C to ET_R. EMR also calculated the drainage water volumes (D) generated by each plot as a consequence of precipitation (D_P) or irrigation (D_I), along with the available useful water in the soil at the beginning (AW_{ini}) and end (AW_{end}) of each day.

~~3.2.~~3.2 Irrigation ~~Q~~quality ~~I~~indices

Net Hydric Needs (NHn), Irrigation Efficiency (IE) and Water Deficit (WD) were applied to evaluate water use in basin D-XIX-6. These indices were calculated from the results obtained by the water balance simulations carried out by EMR.

NHn are defined as the volume of irrigation water required to avoid water stress by the crops and for the soil to remain in the same humidity conditions at the end of the period. NHn are calculated as potential evapotranspiration (ET_C) plus useful water contained in the soil at the end (AW_{end}) minus effective precipitation (P_{ef}) and useful water in the soil at the beginning (AW_{ini}).

$$\mathrm{NHn\,(mm)} = \left(\mathrm{ET_C} + \mathrm{AW_{end}}\right) - \left(\mathrm{P_{ef}} + \mathrm{AW_{ini}}\right)$$

IE quantifies the irrigation percentage that has not been lost through drainage, and is calculated as one minus the relationship between drainage produced by irrigation and total irrigation volume applied:

$$\mathrm{IE}\,(\%) = \left[1 - \left(\mathrm{D_I}/\mathrm{I}\right)\right]\cdot 100$$

Finally, WD evaluates to what extent the hydric needs of the crops have been satisfied, and is calculated as the difference between the potential evapotranspiration (ET_C) of the crop and its real evapotranspiration (ET_R), divided by the potential evapotranspiration (ET_C) of the crop:

$$\mathrm{WD}\,(\%) = \left[\left(\mathrm{ET_C} - \mathrm{ET_R}\right)/\mathrm{ET_C}\right]\cdot 100$$

~~3.3.~~3.3 Statistical calculations

The temporal evolution of irrigation management throughout the period 1998~~-~~–2012 was carried out through a cluster multivariate statistical analysis (Hair et al., 1999), which classified the years in function of annual values of IE, WD and NHn. Cluster analysis was accomplished with standardized data, using the Euclidean square distance as similarity measure. The Ward method was followed to obtain hierarchic conglomerates (Hair et al., 1999).

When comparing different data families for IE, WD and NHn in different crops, firstly it was verified whether the series were normal. In the case of normal distribution series, family differentiation was accomplished by the comparison of averages, using Tuke's analysis with a ~~less than 5~~< 5% error probability. When the distribution of series was not normal, families were differentiated by comparing medians (Mann and Whitney, 1947; Kruskal and Wallis, 1952), with significantly different series identified with $p < 0.05$.

Trend analysis applied the nonparametric Mann-Kendall test (Kendall, 1975; Mann, 1945) to a statistical significance level of 5%, using Sen's slope to measure trends. This nonparametric statistical procedure was applied because it enables the development of analyses without considering the probability distribution of the data employed, and is more permissible to the occurrence of extreme values or other discontinuities.

~~4.~~4 Results and discussion

~~4.1.~~4.1 Water balance

During the 15 studied years, irrigation was the main water contributor to the zone (65%), with an average value of 712 mm/year. Since irrigation management changes were implemented, the volume of water applied has decreased by 40% (Table 1). Therefore, after implementation of on-demand irrigation, annual irrigation volumes have not surpassed the lowest annual irrigated volume in 1998~~-~~–2001.

Table 1 Inputs due to precipitation (P) and irrigation (I) and outputs due to evapotranspiration (ET_R) and drainage (D) and variation of water in the soil (Available Water, AW) in basin D-XIX-6 in hydrological years 1998–2012. Annual pluviometry classification according to the Standardized Precipitation Index (SPI) and Percent of Normal Precipitation (PNP).

alt-text: Table 1

SPI	PNP %	Year	P mm	I mm	ET_R mm	D mm	AW Mm
− 0,71	− 15	1998	375	934	956	323	+29
+0,30	+ 3	1999	453	785	945	314	− 21
− 2,19	− 30	2000	309	1127	1026	417	− 7
+0,60	+ 9	2001	482	1201	1116	526	+41
− 1,15	− 21	2002	350	585	805	173	− 43
+0,57	+ 9	2003	479	706	1000	179	+6
+1,38	+ 30	2004	581	708	1020	265	+3
− 3,09	− 49	2005	226	611	824	70	− 57
+0,27	+ 2	2006	452	517	758	142	+71
− 0,76	− 16	2007	372	539	776	178	− 44
− 2,34	− 31	2008	305	604	716	176	+16
− 0,14	− 6	2009	415	615	815	235	− 20
− 1,36	− 23	2010	340	615	762	188	+5
− 2,64	− 33	2011	298	554	718	159	− 24
− 3,09	− 63	2012	165	573	640	75	+23
		98–12	374	712	855	228	− 1
		CV %	29	30	16	54	2307
1998–2012		mm/year	− 10 ns*	− 33**	− 25***	− 18**	− 0,4 ns

Statistical significance: ns = not significant.

* $p < 0.05$.

** $p < 0.01$.

*** $p < 0.001$.

Annual average precipitation was 374 mm, lower than historical registries. Only the year 2004 was catalogued as rainy according to SPI and PNP. The remaining 14 years were divided between normal and dry, but in the historical series, normal years constituted 70% of the period, while 17% were dry and 13% rainy (Table 1). The driest year was classified as intense drought, with only 165 mm of precipitation, while the rainiest year presented 581 mm of precipitation, which was almost half the annual water involved in the balance (45%).

Regarding water outputs, evapotranspiration was always the most important component of the balance, with 855 mm/year. Although there was a slight annual variability associated with the distribution of crops, it was low in comparison with the remaining components of the balance. Therefore, the increase in winter cereal at the expense of alfalfa and corn resulted in ET_R reduced by one third (Table 1).

The volume of water drained by the soil was 228 mm/year, with a 72% reduction between 1998 and 2012. The years with higher drainage volumes also presented higher water inputs, while the driest years coincided with lowest inputs, yielding minimal soil drainage (Table 1).

4.2.4.2 Irrigation quality

The NHn measured in the zone for the 15 studied years were 670 mm/year, and although the changes in crop distribution reduced the hydric needs by 8%, this decrease was not significant.

The highest NHn occurred in the years with lowest precipitations during development of crops (2012) or large areas of corn and alfalfa (2001). Minimum NHn (2007, Fig.4) were obtained when large areas were cultivated with corn and alfalfa, with higher-than-average precipitation.

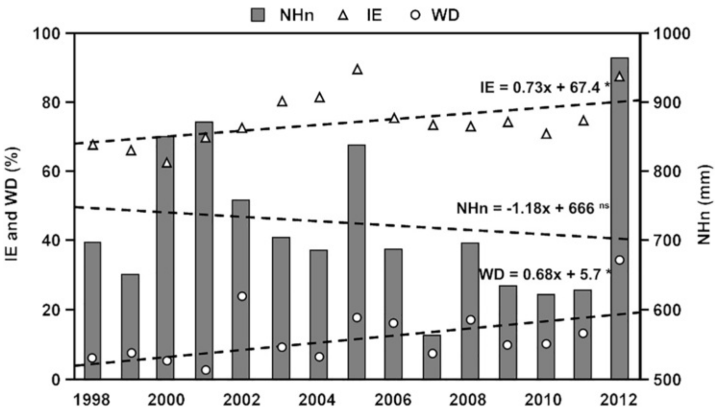


Figure 4.Fig. 4 Annual evolution of Irrigation Efficiency (IE), Water Deficit (WD) and Net Hydric Needs (NHn) in basin D-XIX-6, during 1998–2012. The upper section indicates the slope values and statistical significance: ns = not significant; *$p < 0.05$.

alt-text: Fig. 4

Regarding irrigation, after management changes were implemented, the volumes of water applied were better adjusted to the necessities of the crops. In this way, while between 1998 and 2001 the difference between the water applied and NHn was 295 mm, during the post-change period an average deficit of only 9 mm was recorded between April and September. Annual deficits ranged from -– 153 to -– 357 mm in the dry years 2002, 2005, and 2012.

Average IE was moderate (75%), and it must be noted that the changes in irrigation management improved the efficiency values significantly (Fig. 4). During 1998–2012 the annual efficiency values improved from 60% (at the lowest range of acceptable values for flood irrigation systems; Tanji and Kielen, 2002) before the implementation of changes, similar to efficiency values found in similar Mediterranean irrigation areas (40%: Ucar et al., 2010; 66%: Poch-Massegúa et al., 2014) to efficiency values close to 80%, similar to those obtained in modern irrigation systems (94%, Cavero et al., 2003; 72%, Abrahao et al., 2011a; 72%, Skhiri and Dechmi, 2012; 76%, Andrés and Cuchí, 2014; 76%, Merchán et al., 2015), with 90% values in the dry years of 2005 and 2012.

The IE values for this flood irrigation system presented an advantage in comparison with modern sprinkler systems: although the latter can achieve efficiency values close to 90%, losses due to evaporation and wind drift can add up to 15-–20% of the applied irrigation (Dechmi et al., 2003; Playán et al., 2005; Abrahao et al., 2011a; Merchán et al., 2015).

Regarding WD, although the irrigation volume surpassed the NHn of the crops, these still registered a slight deficit and in consequence, potential decreases in production. In this sense, while in 1998-–2001 the deficits were minimum (6%), after 2003 the WD values were incremented by 15%, reaching 35% in 2012 (driest year of the series), following a 0.7%/year trend (Fig. 4).

The 15 hydrological years were classified according to the cluster analysis in three groups (Table 2). The first group encompassed years 1998 to 2001, characterized by high NHn (656 mm), associated with the implementation of corn and alfalfa. Also, low IE were obtained (66%) along with WD (6%), due to the impossibility of applying irrigation in the most adequate moment (conditioned to the traditional flood irrigation in shifts).

Table 2 Years, annual values for Net Hydric Needs (NHn), Irrigation Efficiency (IE) and Water Deficit (WD) in the study zone, for each of the three groups distinguished by the cluster analysis of the 15 hydrological years in basin D-XIX-6.

alt-text: Table 2

Group		1	2	3
Years		1998, 1999, 2000, 2001	2002, 2003, 2004, 2006, 2007, 2008, 2009, 2010, 2011	2005, 2012
NHn	mm/year	656	517	692

IE	%	66	75	88
WD	%	6	12	27

The second group was mainly constituted by the post-change years (60%). These years presented the lowest NHn (517 mm), moderate-high IE values (75%) and a slight WD from the crops (12%), although this deficit was concentrated on winter cereal.

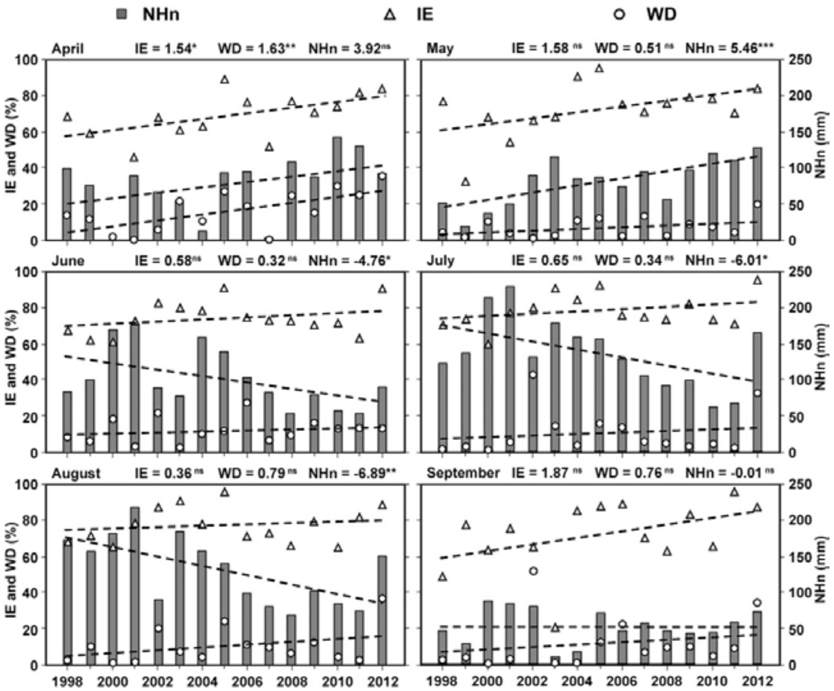
The third and last group was constituted by years 2005 and 2012, classified as the driest years within the study period. These years were characterized by the highest NHn (692 mm), best IE value (88%) as well as highest deficit values (27%).

In this way, the years with highest IE also presented elevated WD values, and despite the fact that on-demand irrigation helped achieve better application efficiencies, it occurred at the expense of a slight increase in water deficit.

Within 1998~~-~~–2012, no variations in the NHn of the crops were detected which could be associated with changes in irrigation management, and positive trends were observed for IE and WD.

~~4.3.~~4.3 Monthly evaluation of irrigation quality

Monthly NHn suffered important changes during the study period, and with the exception of September (no variations), NHn increased moderately in April and May and then decreased from June to August (Fig. 5).



~~Figure 5.~~Fig. 5 Monthly evolution of Hydric Needs (NHn), Irrigation Efficiency (IE) and Water Deficit (WD)in basin D-XIX-6 during the period 1998~~-~~–2012. The upper part indicates the slope values and correspond statistical significance: ns = not significant; *p < 0.05; **p < 0.01; ***p < 0.001.

alt-text: Fig. 5

Such evolution is a consequence of the increase of winter cereal surface, with a growth cycle that extends from November to June, at the expense of corn and alfalfa surfaces, with a development cycle from April to September.

In this way, a greater extension of cultivable land had no occupation in the Summer months, when the implemented crops presented the highest Kc and maximum evapotranspirative demands, reducing NHn from June to August.

Regarding IE, all months presented positive trends, with annual increment rates close to 2% in April, May and September, significantly superior to the Summer months, which did not surpass 1% annually (Fig. 5).

Therefore higher IE were always achieved with low variabilities in Summer (IE ≈ 80%; VC ≈ 12%) in comparison with Spring and Autumn (IE ≈ 70%; VC ≈ 20%). When the evapotranspirative demands of the crops were maximum, at the moment of irrigation the soil was closer to its wilting point, and IE improvements resulted minimal.

The increases in efficiency values were maximum at the beginning and end of the irrigation campaign, when better water control enabled a better adjustment between the lowest hydric needs of the crops and the irrigation applied.

Regarding WD, although the monthly irrigation volumes applied surpassed the hydric needs of the crops, slight deficit values were registered (under 8%), except for the months of April and June.

The water deficit in April was associated with the lack of soil humidity (before the beginning of the irrigation campaign) suffered by some plots cultivated with alfalfa or winter cereal. The latter is not considerably affected as it still was in its post-winter reactivation process.

Although June also presented WD over 8%, variability in the deficit values was the lowest within the series (VC = 56%), which allowed for the assumption of a certain seasonal component. June is when winter cereal is harvested, and the farmers usually "force" a slight deficit in this crop to favor the drying previous to harvesting.

Therefore, although the better availability of water improved the application efficiencies, especially at the beginning of the irrigation campaign, the crops registered a slight water deficit that should be better investigated as positive deficit growth rates were obtained during the study period.

~~4.4.~~4.4 Irrigation quality indices per crop

The highest values of ETc, NHn and irrigation corresponded to alfalfa, followed by corn, sunflower and winter cereal. Of the three variables, ETc presented the lowest annual variability in comparison with NHn and irrigation, both dependents on precipitation.

NHn increased for all crops during the 15 study years, and these increases were related to decreases in precipitation and increase of ET_0 in Spring and Summer, as described by García-Garizábal et al. (2014c), with rates that surpassed 8 mm/year for sunflower and alfalfa (Fig. 6).

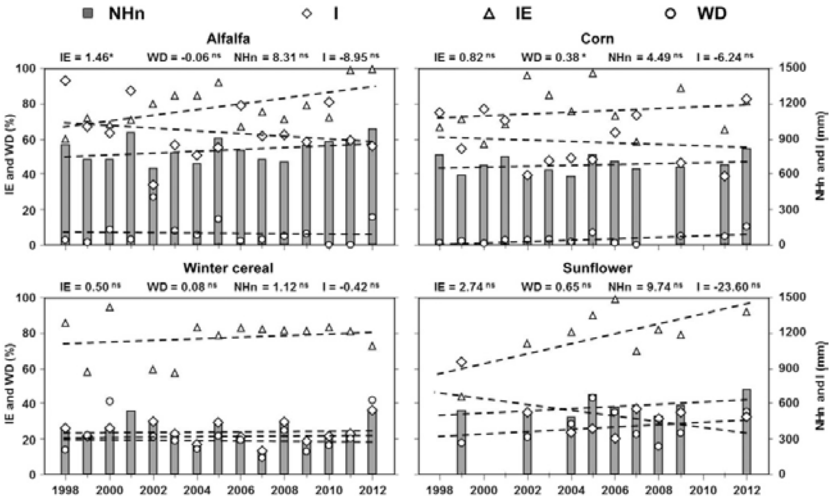


Fig. 6 Yearly evolution of Irrigation Efficiency (IE), Water Deficit (WD), Net Hydric Needs (NHn) and Irrigation (I) in main implemented crops (alfalfa, corn, winter cereal and sunflower) in basin D-XIX-6 during the period 1998-2012. The upper part indicates the slope values and correspond statistical significance: ns = not significant; * p<0.05; ** p< 0.01; *** p< 0.001.

alt-text: Fig. 6

The irrigation applied decreased for all crops, with the most affected being sunflower (– 24 mm/year) and alfalfa (– 9 mm/year), in comparison with corn and winter cereal, with decreases of only – 1 mm/year (Fig. 6).

IE did not present variations across crops, oscillating between 76% for corn and 79% for sunflower, also presenting low variability (VC = 15–21%). Nevertheless, efficiency values increased for all crops since 1998, especially for alfalfa (Fig. 6).

Winter cereal was the crop that suffered the least changes in efficiency values, with a low improvement in IE (0.4%), while sunflower benefitted the most, with annual improvements close to 3%.

WD presented the highest variabilities within the studied variables. While alfalfa and winter cereal presented annual variations close to zero for deficit values, for corn the variation rate was + 0.4% and for sunflower it reached + 0.7% per year.

The farmers always maintained low WD for corn (3%) and alfalfa (7%), while winter cereal and sunflower (more tolerant to water deficit) presented deficit values that were superior and more homogeneous throughout time (WD_{WC} = 21%; $WD_{Sunflower}$ = 27%).

Nevertheless, the years of more intense drought also registered the highest deficit values.

Therefore, although the changes implemented in the basin resulted especially advantageous for alfalfa and winter cereal (improvements in IE and no changes in WD values), corn and sunflower were less influenced by these changes and water deficits were detected and should be conveniently addressed.

~~5.~~5 Conclusions

Implementation of changes in water management at the studied irrigation area contributed to a reduction in the volumes of irrigation applied (40%) and in drainage (72%).

With the new irrigation management, a better adjustment has been produced between the hydric needs of the crops and the volumes of water applied by the farmers, in such a way that irrigation efficiencies also improved up to 80%, with only a slight increment of water deficit.

At a monthly scale, control of irrigation doses enabled the improvement of application efficiencies at the beginning and at the end of the irrigation campaign. Although slight deficit values were detected, a seasonal component was verified, associated with the management by farmers.

When analyzing individual crops, although the possibility of better water management by the farmers has improved irrigation efficiency values for all implemented crops, small negative trends were detected in the evolution of water deficit for corn and sunflower, which should be improved.

In this way, although the changes implemented in water management at this flood-irrigated basin have enabled the increase of irrigation efficiency up to values found in pressurized irrigation systems (especially in stages of low hydric needs, as it allows for a better adjustment between water demands and applied doses), specific episodes of water deficits still occur, which should be remediated.

Acknowledgments

This study has been financed by project 2012/GA LC 016 (Aragón Government and La Caixa), by the Geological Survey of Spain, and by project PROMETEO 20140480BP from the National Secretary of Superior Education, Science, Technology and Innovation (SENESCYT).

References

Abrahao R., Causapé J., García-Garizabal I. and Merchán D., Implementing irrigation: water balances and irrigation quality in the Lerma Basin (Spain), ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **102**, 2011a, 97–104.

Abrahao R., Sarasa J., Causapé J., García-Garizábal I. and Ovelleiro L., Influence of irrigation on the occurrence of organic and inorganic pollutants in soil, water and sediments of a Spanish agrarian basin (Lerma), *Span. J. Agric. Res.* **9**, 2011b, 124–134.

Allen R., Pereira L., Raes D. and Smith M., Crop evapotranspiration. Guidelines for computing crop water requirements, In: *FAO Irrigation and Drainage Paper n° 56,* 1998, Food and Agriculture Organization of the United Nations. Rome.

Alvarez-Coque J.M.G., In: Alvarez-Coque José María García, (Ed), *Changes in the Community Agricultural Policy: Questions and Answers Towards the Future of Agriculture (La reforma de la Política Agraria Común: preguntas y respuestas en torno al futuro de la agricultura),* 2006, Ministerio de Agricultura, Alimentación y Medio Ambiente-Eumedia; Madrid.

Andrés R. and Cuchí J.A., Analysis of sprinkler irrigation management in the LASESA district, Monegros (Spain), *Agric. Water Manag.* **131**, 2014, 95–107, http://dx.doi.org/10.1016/j.agwat.2013.09.016.

Barros R., Isidoro D. and Aragüés R., Long-term water balances in La Violada Irrigation District (Spain): I. Sequential assessment and minimization of closing errors, *Agric. Water Manag.* **102**, 2011, 35–45.

Bustos A., Caballero R. and Roman R., Net changes of main ions in the soil profile of irrigated field plots in central Spain, *Irrig. Sci.* **25**, 2006, 1–9.

Caballero R., Bustos A. and Roman R., Soil salinity under traditional and improved irrigation schedules in central Spain, *Soil Sci. Soc. Am. J.* **65**, 2001, 1210–1218.

Causapé J., A computer-based program for the assessment of water-induced contamination in irrigated lands, *Environ. Monit. Assess.* **158**, 2009, 307–314, http://dx.doi.org/10.1007/s10661-008-0584-z.

Causapé J., Quílez D. and Aragüés R., Assessment of irrigation and environmental quality at the hydrological basin level—I. Irrigation quality, *Agric. Water Manag.* **70**, 2004a, 195–209.

Causapé J., Quílez D. and Aragüés R., Assessment of irrigation and environmental quality at the hydrological basin level—II. Salt and nitrate loads in irrigation return flows, *Agric. Water Manag.* **70**, 2004b, 211–228.

Cavero J., Beltrán A. and Aragüés R., Nitrate exported in the drainage water of two sprinkler irrigated watershed, *J. Environ. Qual.* **32**, 2003, 916–926.

CEDEX, Evaluation of the ~~i~~Impact of ~~c~~Climate ~~c~~Change in ~~n~~Natural ~~r~~Regime ~~w~~Water ~~r~~Resources Evaluación del impacto del cambio climático en los recursos hídricos en régimen ~~n~~Natural, 2013, Ministerio de Medio Ambiente y Medio Rural y Marino; Madrid.

Dechmi F., Playán E., Cavero J., Faci J.M. and Martinez-Cob A., Wind effects on solid set sprinkler irrigation depth and yield of maize (*Zea mays*), *Irrig. Sci.* **22**, 2003, 67–77.

Diaz ~~RJ~~R.J., Overview of hypoxia around the world, *J. Environ. Qual.* **30**, 2001, 275–281.

Duncan R.A., Bethune M.G., Thayalakumaran T., Christen E.W. and McMahon T.A., Management of salt mobilisation in the irrigated landscape. A review of selected irrigation regions, *J. Hydrol.* **351**, 2008, 238–252.

FAO, Unlocking the Water Potential of Agriculture, 2003, Food and Agriculture Organization of the United Nations, (http://www.fao.org/DOCREP/006/Y4525S/Y4525S00.HTM (accessed 01.05.16)).

FAO, Agricultural Outlook 2006~~-~~–2015, 2006, Food and Agriculture Organization of the United Nations, (ftp://ftp.fao.org/docrep/fao/009/a0621e/a0621e00.pdf (accessed 01.05.16)).

Feng Z.Z., Wang X.K. and Feng Z.W., Soil N and salinity leaching after the autumn irrigation and its impact on groundwater in Hetao Irrigation District, China, *Agric. Water Manag.* **71**, 2005, 131–143.

García-Garizábal I. and Causapé J., Influence of irrigation water management on the quantity and quality of irrigation return flows, *J. Hydrol.* **385**, 2010, 36–43.

García-Garizábal I., Causapé J. and Abrahao R., Application of the ~~I~~irrigation ~~L~~land ~~E~~environmental ~~E~~evaluation ~~T~~tool for flood irrigation management and evaluation of water use, ~~*CATENA*~~*Catena* **87**, 2011, 260–267.

García-Garizábal I., Causapé J. and Abrahao R., Irrigation management and pollution by salts and nitrate: flood vs. pressurized system (*El manejo del riego y la contaminación por sales y nitrato: un caso de inundación vs. aspersión*), **108**, 2012a, ITEA, 1–19.

García-Garizábal I., Causapé J. and Abrahao R., Nitrate contamination and its relationship with flood irrigation management, *J. Hydrol.* **442**, 2012b, 15–22.

García-Garizábal I., Auqué L.F., Gimeno M.J. and Causape J., Salinity contamination response to changes in irrigation management. Application of geochemical codes, *Span. J. Agric. Res.* **12**, 2014a, 376–387, http://dx.doi.org/10.5424/sjar/2014122-4694.

García-Garizábal I., Causapé J. and Abrahao R., Changes in irrigation management and quantity and quality of drainage water in a traditional irrigated land, *Environ.* ~~*Earth Science*~~*Earth Sci.* **72**, 2014b, 233–242, http://dx.doi.org/10.1007/s12665-013-2949-z.

García-Garizábal I., Causapé J., Abrahao R. and Merchán D., Impact of ~~C~~climate ~~C~~change on Mediterranean ~~I~~irrigation ~~D~~demand: ~~H~~historical ~~D~~dynamics of ~~C~~climate and ~~F~~future ~~P~~projections, ~~*Water Resour. Manage.*~~*Water Resour. Manag.* **28**, 2014c, 1449–1462, http://dx.doi.org/10.1007/s11269-014-0565-7.

García-Vera M.A. and Martínez-Cob J.A., Review of the ~~n~~Net ~~h~~Hydric ~~n~~Needs of the ~~c~~Crops of the Ebro ~~b~~Basin (Revisión de las necesidades hídricas netas de los cultivos de la Cuenca del Ebro), 2004, Confederación Hidrográfica del Ebro; Zaragoza.

Gehl R.J., Schmidt J.P., Stone L.R., Schlegel A.J. and Clark G.A., In situ measurements of nitrate leaching implicate poor nitrogen and irrigation management on sandy soils, *J. Environ. Qual.* **34**, 2005, 2243–2254.

Gkiougkisa I., Kalliorasb A., Pliakasa F., Pechtelidisa A., Diamantisa V., Diamantisa I., Ziogasa A. and Dafnisa I., Assessment of soil salinization at the eastern Nestos River Delta, N.E. Greece, *Catena* **128**, 2015, 238–251, http://dx.doi.org/10.1016/j.catena.2014.06.024.

IPCC, In: Core Writing Team, Pachauri R.K. and Reisinger A., (Eds.), *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* 2007, IPCC; Geneva.

IPCC, Climate ~~c~~Change and ~~w~~Water, 2008, Cambridge University Press; Cambridge.

Isidoro D., Quílez D. and Aragüés R., Water balance and irrigation performance analysis: La Violada irrigation district (Spain) as a case study, ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **64**, 2004, 123–142.

Isidoro D., Quílez D. and Aragüés R., Environmental impact of irrigation in La Violada District (Spain): I. Salt export patterns, *J. Environ. Qual.* **35**, 2006, 766–775.

Isla R. and González T., Utilization of nitrification inhibitors in corn crops cultivated in soils with high runoff potential in Aragón irrigated areas (Utilización de inhibidores de la nitrificación en el cultivo de maíz en suelos de alto potencial de lavado en regadíos de Aragón), 2006, XI Simposio Ibérico sobre Nutrición mineral de las Plantas; Pamplona.

Kendall M.G., Rank ~~c~~Correlation ~~m~~Method, 1975, Griffin; London.

Keyantash J. and Dracup J., The quantification of drought: an evaluation of drought indices, *Bull. Am. Meteorol. Soc.* **83**, 2002, 1167–1180.

Kruskal W.H. and Wallis W.A., Use of ranks in one-criterion variance analysis, *J. Am. Stat. Assoc.* **47**, 1952, 583–621.

Lecina S., Playán E., Isidoro D., Dechmi F., Causapé J. and Faci J.M., Irrigation evaluation and simulation at the irrigation ~~D~~district V of Bardenas (Spain), ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **73**, 2005, 223–245.

Li X.X., Hu C.S., Delgado J.A., Zhang Y.M. and Ouyang Z.Y., Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in north China plain, ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **89**, 2007, 137–147.

Liu Mx, Yang ~~JS~~J.S., Li X., Liu ~~GM.~~G.M., Yu M. and Wang J., Distribution and dynamics of soil water and salt under different drip irrigation regimes in northwest China, *Irrig. Sci.* **31**, 2012, 675–688, http://dx.doi.org/10.1007/s00271-012-0343-3.

Mann H.B., Nonparametric test against trend, *Econometrica* **13**, 1945, 245–259.

Mann H.B. and Whitney D.R., On a test of whether one of two random variables is stochastically larger than the other, *Ann. Math. Stat.* **18** (1), 1947, 50–60.

Martínez-Cob A. and Tejero-Juste M., A wind-based qualitative calibration of the Hargreaves ET_0 estimation equation in semiarid regions, ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **64**, 2004, 251–264, http://dx.doi.org/10.1016/S0378-3774(03)00199-9.

McKee T.B.N., Doesken J. and Kleist J., The relationship of drought frequency and duration to time scales. Eight conference on applied climatology, *Am. Meteorol. Soc.* 1993, 179–184, (Anaheim, CA).

Merchán D., Causapé J., Abrahao R. and García-Garizábal I., Assessment of a newly implemented irrigated area (Lerma Basin, Spain) over a 10-year period. I: water balances and irrigation performance, *Agric. Water Manag.* **158**, 2015, 277–287, http://dx.doi.org/10.1016/j.agwat.2015.04.016.

Petrovic M., Ginebreda A., Acuña V., Batalla R.J., Elosegi A., Guasch H., de Alda M.L., Marcé R., Muñoz I., Navarro-Ortega A., Navarro E., Vericat D., Sabater S. and Barceló D., Combined scenarios of chemical and ecological quality under water scarcity in Mediterranean rivers, *TrAC Trends Anal. Chem.* **30**, 2011, 1269–1278.

Playán E., Salvador R., Faci J.M., Zapata N., Martínez-Cob A. and Sánchez I., Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals, ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **76**, 2005, 139–159.

Poch-Massegúa R., Jiménez-Martínez J., Wallisc K.J., Ramírez de Cartagenaa F. and Candelad ~~L~~L., Irrigation return flow and nitrate leaching under different crops and irrigation methods in Western Mediterranean weather conditions, *Agric. Water Manag.* **134**, 2014, 1–13, http://dx.doi.org/10.1016/j.agwat.2013.11.017.

Roman R., Caballero R. and Bustos A., Field water drainage under traditional and improved irrigation schedules for corn in central Spain, *Soil Sci. Soc. Am. J.* **63**, 1999, 1811–1817.

Scavia D. and Bricker S.B., Coastal eutrophication assessment in the United States, *Biogeochemistry* **79** (1~~-~~–2), 2006, 187–208.

Skhiri A. and Dechmi F., Impact of sprinkler irrigation management on the Del Reguero river (Spain). I: water balance and irrigation performance, *Agric. Water Manag.* **103**, 2012, 120–129, http://dx.doi.org/10.1016/j.agwat.2011.11.003.

Spalding R.F., Watts D.G., Schepers J.S., Burbach M.E., Exner M.E., Poreda R.J. and Martin G.E., Controlling nitrate leaching in irrigated agriculture, *J. Environ. Qual.* **30**, 2001, 1184–1194.

Tanji K.K. and Kielen N.C., Agricultural drainage water management in arid and semi-arid areas, In: *FAO Irrigation and Drainage Paper n° 61,* 2002, Food and Agriculture Organization of the United Nations. Rome.

Tedeschi A., Beltrán A. and Aragüés R., Irrigation management and hydrosalinity balance in a semi-arid area of the middle Ebro river basin (Spain), ~~*Agric. Water Manage.*~~*Agric. Water Manag.* **49**, 2001, 31–50.

Thayalakumaran T., Bethune M.G. and McMahon T.A., Achieving a salt balance should it be a management objective?, *Agric. Water Manag.* **92**, 2007, 1–12, http://dx.doi.org/10.1016/j.agwat.2007.05.004.

Thayalakumaran T., Bristow K.L., Charlesworth P.B. and Fass T., Geochemical conditions in groundwater systems: implications for the attenuation of agricultural nitrate, *Agric. Water Manag.* **95**, 2008, 103–115, http://dx.doi.org/10.1016/j.agwat.2007.09.003.

Ucar Y., Senyigit U., Kadayifci A. and Tuylu G.I., Evaluation of water use efficiency at parcel and scheme levels: ~~A~~a case study of Sarkikaraagac irrigation scheme in Turkey, *J. Food Agric. Environ.* **8**, 2010, 1046–1053.

Wang B., Cultural eutrophication in the Changjiang (Yangtze River) plume: ~~H~~history and perspective, *Estuar. Coast. Shelf Sci.* **69**, 2006, 471–477.

Highlights

- Irrigation was evaluated in an agricultural basin after changes in water management.
- Analyses included climatic and agronomic variabilities and irrigation quality indices.
- The investigation includes long-term monitoring throughout 15 hydrological years.
- Changes contributed to improve irrigation efficiency and drainage reduction.
- Water deficit episodes were detected that should be remediated.

Queries and Answers

Query:

Please provide caption.

Answer: Caption has been added. Thank you.

Query:

Please check the layout and presentation of Tables 1 and 2 if correct.

Answer: Tables have been reviewed and modified. The major issue was related to remove "* p<0.05" because it is not in the table. On the other hand, "+" signs have been inluded in columns SPI, PNP and AW. Thus, there was a typewriting mistake in P in year 2006, and the corect vale is 452. Thank you.

Query:

Footnote “*” was not cited in Table 1. Hence, a dummy footnote citation was added here. Please check for proper placement and amend as necessary.

Answer: OK, If necessary, remove de line below "* p< 0,05" because "*" is not used in table 1. Thank you.

Query:

Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact s.vadivelan@elsevier.com immediately prior to returning your corrections.

Answer: The article is a regular item. Thank you.

Query:

There was no affiliation provided for author “D. Merchán” in the manuscript. Nonetheless, we have opted to link the author to affiliation “b”. Kindly verify if the action taken is appropriate. If otherwise, please include the appropriate affiliation along with the corrections. Thank you.

Answer: The author D. Merchan doesn't belong to IGME, he is an independent researcher and doesn't have affiliation. However, corresponding author has now 2 affiliations, and the new one is "[c] Center of Alternative and Renewable Energy, Department of Renewable Energy Engineering, Federal University of Paraiba, Cx Postal 5115, 58051-900, João Pessoa, Paraíba, Brazil"

Query:

The author names have been tagged as given names and surnames (surnames are highlighted in teal color). Please confirm if they have been identified correctly.

Answer: Author names were identified correctly. Thank you.

Query:

Please check whether the designated corresponding author is correct, and amend if necessary.

Answer: The corresponding author is correct. Thank you.

Query:

An e-mail address is mandatory for corresponding authors; however, private e-mail addresses (e.g., gmail, hotmail, yahoo) should not be included. Please check if an alternative institutional e-mail address can be provided for the corresponding author/s.

Answer: ikerggarizabal@gmail.com

Query:

Please check the hierarchy of the section headings and confirm if correct.

Answer: It is correct. Thank you.

Query:

The citation "Abrahao et al., 2011" has been changed to "Abrahao et al., 2011a, 2011b" to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

Answer: Abrahao et al., 2011 is Abrahao et al., 2011a

Query:

The citation "Causapé et al., 2004" has been changed to "Causapé et al., 2004a, b" to match the author name/date in the reference list. Please check if the change is fine in this occurrence.

Answer: Causapé et al., 2004 is Causapé et al., 2004a

Query:

The citation "García-Garizábal et al., 2012" has been changed to "García-Garizábal et al., 2012a, b" to match the author name/date in the reference list. Please check if the change is fine in this occurrence.

Answer: García-Garizábal et al., 2012 is García-Garizábal et al., 2012a

Query:

Citation "Hair et al., 1999" has not been found in the reference list. Please supply full details for this reference.

Answer: Hair, J., Anderson, R., Tatham, R., Black, W., 1999. Análisis multivariante, fifth ed, Prentice Hall Iberia, Madrid.

Query:

Please provide the corresponding grant number(s) for the following grant sponsor(s): "Geological Survey of Spain" and "SENESCYT".

Answer: Geological Survey of Spain financiation was related to the usage of vehicles, electricity, personal computer... and there was not an exact project to include here. Reference number of project PROMETEO is 20140480BP