WATER AND ENERGY MANAGEMENT IN AN AUTOMATED IRRIGATION DISTRICT

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ABSTRACT

An important modernization process providing pressurized irrigation systems to the traditional surface irrigation districts has taken place in Spain over the last 20 years. This modernization process has been promoted by the central government and the Autonomous Communities of Spain with the goals of water conservation and the sustainability of irrigated lands. The farmers who have to pay a large portion of the cost have happily accepted the modernization process mainly because of the important reductions of the labor that is required to perform the irrigation tasks, the mechanization of the crop and the improvement of the crop yields. However, an adverse consequence of modernization is the important increase in the energy cost in the modernized irrigation districts, which is aggravated by the current high energy prices. The Almudévar irrigation district (AID), a traditional surface irrigation district, was transformed into a pressurized sprinkler irrigation system in late 2010. The irrigation network was equipped with a high-level telemetry and remote control system that reaches the hydraulic valves of the irrigated blocks into which the plots are divided. Therefore, the telemetry system enables the centralized management of the irrigation scheduling from the district office. The district is divided into four independent networks with their own reservoirs and electric pump stations. A comparison of the land structure, crop patterns and irrigation management between the modernized AID in 2011 and the pre-modernization AID in 2006-2008 was performed. The temporal evolution of the irrigation water and energy demands in the 2011 irrigation season was analyzed with the available telemetry data from 2011. An irrigation performance index (SIPI) of the monthly and seasonal frequencies was computed for the main crops of the AID. Most of the irrigation events were observed during the weekend due to the low electricity. The irrigation patterns showed a more significant relationship with the energy tariff schedule than with the meteorological constraints due to the centralized irrigation scheduling. The exploitation of telemetry data has been considered necessary to improve the water and energy management and to control the irrigation cost. Additionally, the telemetry data analysis has been an important decision-making tool in optimizing the contracted electricity power in each tariff period and in decreasing the electric bill of the AID.

Keywords: Telemetry, Remote control systems, Irrigation water use efficiency, Energy efficiency.

I. INTRODUCTION

In the last two decades, the economic growth in Spain has greatly increased the water demand; however, the water availability has not increased due to the lack of significant increases in the water storage capacity (MARM 2006). The Spanish government has introduced several changes to manage the water demand, such as public water rights banks, environmental taxes and subsidies for irrigation modernization (Lecina et al., 2010a, b). In addition, new water management plans are being implemented through a participatory and integrated process following the guidelines of the European Water Framework Directive (Lecina et al., 2010a).

One of the most important actions in improving the water resources management is the irrigation modernization process that was developed through the two National Irrigation Modernization Plans (*Plan Nacional de Regadíos* and *Plan de Choque de Modernización de Regadíos*) (MARM, 2002; MARM, 2006). The main objectives of these plans are the conservation of water to increase the water resources for irrigation or alternative uses and the sustainability of Spanish irrigated lands (MARM 2010). As a result of these irrigation modernization plans, sprinkler irrigation areas have increased in Spain. According to the 2011 Areas and Crop Yields Survey (ESYRCE) (M.A.A.M.A., 2012), the total irrigated area in Spain is 3,473,474 ha, of which 497,794 ha are sprinkler-irrigated.

Irrigation modernization usually involves the replacement of open-channel gravity systems by pressurized irrigation pipe distribution networks with a hydrant in each farm. Additionally, modern telemetry and remote control systems are incorporated into the majority of the modernized collective irrigation networks in Spain. This type of infrastructure provides many opportunities for the improvement of irrigation management (Stambouli et al., 2012). The new networks enable a more efficient water application with irrigation systems, such as drip and sprinkler irrigation, instead of surface irrigation (Playán and Mateos, 2006). Lecina et al. (2010a) reported that a consequence of irrigation modernization could be an increase in the consumptive water use due to more intensive cropping. Another important consequence of irrigation modernization is the increase in the energy consumption and, therefore, the increase in the irrigation energy cost. However, the use of pressurized irrigation systems has drastically decreased the labor cost of irrigation. From 1970-2007, Corominas (2010) reported that the water that was used for on-farm irrigation in Spain decreased by 21%, from 8250 to 6500 $m^3 ha^{-1}$, but the energy consumption increased by 657%, from 206 to 1560 KWh ha^{-1} (Abadía et al., 2012).

Due to the 2008 liberalization of the electricity market in Spain and the elimination of special rates for irrigation, the average energy costs in the modernized irrigation districts have sharply increased. For example, the average electric energy cost in a few irrigation districts in northern Spain increased by 82% between 2005 and 2009 (Ederra and Murugarren, 2010; Abadía et al., 2012). The high contribution of energy to the total irrigation cost has led to the publication of numerous studies and methodologies to quantify and improve the energy efficiency (Carrillo-Cobo et al., 2010; Moreno et al., 2010; Rodriguez-Díaz et al., 2009; Lamaddalena and Khila, 2012).

Due to the high energy cost in the pressurized irrigation districts, it is necessary to operate the whole district with a maximum energy efficiency. It is not enough to apply irrigation according to the crop water requirements; it is also necessary to irrigate during low-cost electricity periods, maintaining a high efficiency in the pumping stations.

Many irrigation performance analyses characterizing the irrigation efficiency in the pressurized irrigation districts can be found in the literature (Faci et al., 2000; Dechmi et al., 2003; Lorite et al., 2004a, b; Stambouli et al., 2012; Salvador et al., 2011). All of these works found a high spatial variability of the irrigation performance indicators and concluded that the variability between the farms indicates a potential for improvement. These analyses are complex, but they are needed to minimize the cost of energy per unit of water applied. Fortunately, telemetry and remote control systems provide the necessary data (Stambouli et al., 2012).

The sharp rise in electricity and agricultural input (fertilizers, seeds, pesticides, etc.) costs, together with fluctuating crop prices, can threaten the profitability of irrigated farms mainly in the recently modernized districts. Lecina et al. (2010a) stated that the results that are obtained post-modernization will also depend on factors other than irrigation, such as the evolution of agricultural and energy costs. To optimize the irrigation scheduling and power costs in the irrigation districts, analytical tools should be used to make appropriate decisions under different situations. A substantial investment has been made in the new pressurized irrigation network design so that it can operate under on-demand delivery schemes. The on-demand scheme offers the greatest potential to optimize the irrigation scheduling (Lamaddalena and Sagardoy, 2000). This type of delivery scheme is highly dependent on farmer skills as they make the irrigation decisions. The increase in the energy demands and, above all, the significant increase in the energy costs in recent years have changed the perception of this delivery scheme. The knowledge that is needed to cope with economic, technical and environmental constraints cannot be amassed by individual farmers. Authors such as Rodriguez Díaz et al. (2009) and Moreno et al. (2010) have proposed solutions based on optimizing technical issues, such as the pumping efficiency and hydraulic performance. Other authors, such as Zapata et al. (2007; 2009), have proposed solutions based on using simulation tools to drive the telecontrol systems. This study was performed in an irrigation district, the Almudévar Irrigation District (AID), which was recently modernized from a surface to a pressurized irrigation system. This district is one of the most innovative irrigated areas as it has incorporated new sprinkler irrigation systems, the highest technological telemetry and remote control systems that control the low-level element (the valves of the hydrant's irrigated blocks). Due to its electrical dependence and the high investment cost, the modernized district requires a high standard of water and energy management to be competitive. The future water and energy limitations and high prices will trigger the exploitation of new technologies to improve the irrigation management standards (Evans and King, 2012). This study presents an analysis of the current water and energy management of the AID and indicates the difficulties in coping with all of the constraints in maximizing the farm income.

The specific objectives of this study were as follows: 1) to analyze the seasonal and monthly on-farm irrigation performances at the plot level by assessing the continuous irrigation performance index (SIPI) and to compare these performances with those pre-modernization; 2) to characterize the irrigation scheduling patterns that are related to meteorology and to the energy cost structure; and 3) to exploit the telemetry data records to improve the water management and optimize the irrigation cost.

II. MATERIAL AND METHODS

II.1. The Almudévar Irrigation District evolution

The study area was the Almudévar Irrigation District (AID), which is located in the Ebro River Basin in northeastern Spain in the autonomous community of Aragón, which has the fourth largest irrigated area in Spain after Andalucía, Castilla La Mancha and Castilla Leon (M.A.A.M.A, 2012).

The district occupies 3,744 ha of irrigated land and is integrated into the Monegros I irrigation scheme. Until 2008, 94% of the AID area was surface-irrigated with blocked-end plots, 5% was sprinkler-irrigated and 1% was drip-irrigated. The AID irrigation system was originally designed to irrigate winter cereal, and the capacity of the irrigation ditches was very limited (Faci et al., 2000; Playán et al., 2000). Consequently, the proportion of summer crops in the district was limited, and very often, the summer crops suffered some degree of water stress due to the irrigation intervals being very long.

The modernization process that was completed in 2010 transformed the entire irrigation system from surface to pressurized (94% of the area with solid-set, 5% with center pivots and lateral move systems and 1% with drip irrigation systems). The first phase of the AID modernization process was land consolidation. As a result, a farmer would get a single plot in the district with an area that was similar to the sum of the plots that he owned before the consolidation. The former district was characterized by a high number of part-time farmers, with only 20% of the farmers being fully dedicated to agriculture. Even after the modernization process, the part-time farmers are numerous, and plot leasing is very common. The changes in the land ownership and tenure structure were analyzed.

The modernized AID was divided into four independent irrigated zones, including three independent irrigated networks (Abariés, Colladas and Matilero) and two interconnected irrigated networks (Violada and Artical) that will be referred to one irrigated zone (Violada-Artical). Each zone has its own reservoir, its own electric pumping station and its own distribution pipe network. The total storage capacity of the AID is 635,160 m^3. The total installed pumping power is 6,361 kW, enabling a maximum flow rate of 6,000 L s^{-1}. This flow is sufficient for simultaneously supplying water to 60% of the AID area. From the district control center, a programmable robot remotely manages the operation of the pumping stations and the associated electromechanical systems.

The second part of the modernization process was the construction of the shared irrigation network infrastructure. The network brings the water to the hydrants, which are located in each farm at an average pressure of 400 kPa. The accomplishment of the on-farm irrigation systems was also executed collectively by the water user association. This accomplishment has homogenized the on-farm irrigation system design. In the AID, the solid sets (94% of the area) have a triangular arrangement of 18 m between the sprinkler lines and 18 m between the sprinklers. The impact sprinklers were installed 2 m aboveground and were equipped with a double nozzle with inside diameters of 4.4 mm and 2.4 mm. The on-farm systems were designed to operate at an average nozzle pressure of 300 kPa, which represents a design irrigation precipitation of 5.3 mm h^{-1}.

The new infrastructure was equipped with a high-level technological telemetry and remote control system (TM/RC) that enables the remote management of all of the hydraulic valves (290 hydrants valves and 2,200 irrigation block valves) in the irrigation networks (collective and on-farm) from the district office. The collective irrigation system operates in an organized on-demand scheme. The irrigation scheduling of all of the irrigation blocks was performed by the district manager, considering farmer preferences, the hydraulic capacity of the pipe network, the variation in the electricity costs over days and months and the available contracted power. The farmers communicate their irrigation preferences (irrigation hours and days of the week) to the manager with a daily or weekly frequency. The district manager manually introduces the irrigation starting times and the duration of the system's 2,490 valves using the programmable robot of the TM/RC system that is located in the central district office.

The TM/RC system consists of a control center unit (PC unit) that communicates via a wireless radio with the communications center that is located at the highest point of the AID (Almudévar Castle Tower). From this point, the irrigation schedules, which are manually programmed by the district manager in the control center unit, are sent to seven control subunits that are responsible for remotely distributing the corresponding commands to the hydrants and irrigation block valves. Each control subunit has a memory card, enabling the accumulation of over 200 schedules. The system continuously produces (every 10 minutes) a "refreshment" of information (update) by radio ordering the hydrant situation (open or close a general hydrant; open or close a determined irrigation block hydraulic valve, etc.).

The TM/RC was set to operate at three levels: hydrant, plot and irrigation block (IB, area that is irrigated simultaneously by a hydrant). The TM/RC system in the AID is one of the most advanced systems compared with those that have been installed in other modernized irrigation networks because the remote control reaches the last level of control, the irrigated block valves. The system stores the volume and duration of each irrigation event for each hydraulic valve. The pressure at the control points in the pipe network was also recorded. The pressure and discharge data at selected points were used to supervise the control network status and incidences (breakdowns, opening and closing of the hydraulic valves, etc.).

II.2. Meteorological characteristics and irrigation performance

The agro-meteorological station (http://www.mapa.es/siar/Informacion.asp) named Tardienta Station (41º 58´ 14´´ N; 0º 30´ 24´´ W) was used for the meteorological characterization of the AID. The mean annual values of the principal meteorological variables include an air temperature of 13.6 °C (23.7 °C for July and 4.3 °C for December) and an annual precipitation of 348 mm. The predominant wind directions are northwest (locally denominated *Cierzo*, dry and cold) and southeast (locally denominated *Bochorno*, dry and hot) with a mean annual wind speed 2 m aboveground of 2.6 m s^{-1}. According to Martínez-Cob et al. (2010), these characteristics describe a moderate wind area. The semi-hourly values of air temperature (T), air relative humidity (RH), wind speed (U) and precipitation (P) were compared with the amount of irrigation water that was applied throughout the 2011 irrigation season in the AID.

The reference evapotranspiration (ET_0) was computed daily using the Penman-Monteith method (Smith 1993). The average annual value of the ET_0 was 1,285 mm. The crop evapotranspiration (ET_c, equation 1) was estimated from the ET_0 and the appropriate crop coefficients (K_c).

$$ET_c = K_c \; ET_0 \tag{1}$$

The K_c values of the main crops of the AID, except for maize, were taken from Allen et al. (1998) and complemented with local information. The K_c values of maize were estimated using the thermal unit methodology that was proposed by Martínez-Cob (2008) for the Ebro Valley region. The net irrigation requirements of the main crops of the AID for the 2011 irrigation season (NIRs, equation 2) were calculated using the standard FAO procedures as described by Allen et al. (1998). The effective precipitation (EP) was calculated using the empirical USDA method (Cuenca, 1989).

$$NIR = \left(K_c \; ET_0\right) - EP \tag{2}$$

The performance parameter that was used to characterize the water use in the AID was the Seasonal Irrigation Performance Index (SIPI) (Faci et al., 2000). The SIPI was defined (equation 3) as the relation of the seasonal net irrigation requirements (NIRs, mm) to the percentage of the seasonal irrigation depth that was delivered to the crops (ID, mm). The SIPI values were calculated on a monthly (or cuts for alfalfa crop) and seasonal basis for the main crops of the AID in 2011. The monthly and seasonal irrigation depths delivered to the crops were obtained from the telecontrol records. The SIPI values represent a simplification of the irrigation efficiency standard concept that was defined by Burt et al. (1997). Considering an average value of 15% for the wind drift and evaporation losses in the solid-set sprinkler irrigation (Playán et al., 2005), a value of SIPI of approximately 85 % would indicate a very high irrigation efficiency. Values of SIPI above 100% would indicate under-irrigation, while those below 60% would indicate over-irrigation. The spatial and temporal variabilities of the index were analyzed for each crop.

$$SIPI = \frac{Net\ irrigation\ requirements\ (NIR)}{Irrigation\ depth\ (ID)} * 100 \quad (3)$$

II.3. Analysis of the solid-set irrigation patterns in the AID

The TM/RC records from the 2011 irrigation season were used to characterize the irrigation patterns at the hydrant and IB levels. The seasonal number of irrigation events, the irrigation starting time, the seasonal irrigation time, the seasonal irrigation depth, the time interval between irrigation events, the irrigation sequence of the irrigated blocks composing a plot, the time and depth of each irrigation event, and the changes in the irrigation schedules throughout the crop season were determined. The changes in the irrigation schedules were analyzed, dividing the crop season into two periods with significant differences in the irrigation requirements, the first period from April to June and the second period from July to August.

II.4. Analysis of the adequacy of the power contracted during each energy tariff period

The pumping stations in the AID use electric pumps with frequency regulators to adapt the water supply to the water demand, maintaining a high energy efficiency throughout the irrigation season. The AID, as with other water user associations in Spain, has an electricity supply contract that is arranged in six tariff levels that are characterized by very different energy (Kwh) and power (Kw) costs. The Kwh cost of the cheapest tariff (P6) represents 38% of the most expensive tariff (P1). The Kwh costs of the tariffs P2 to P5 are between the values of P1 and P5. The energy tariff time distribution is very complex and changes throughout the day and months (Figure 1). The Kw cost also changes with each tariff. The cost per Kw in the P6 tariff is 17% of the P1 tariff. The cheapest electricity period (P6) was operative during all of the night-time periods from 00:00 to 08:00, the entire weekend (Saturday and Sunday), National Festive days and all of August. The most expensive electricity period (P1) was only operative during the daytime periods from 11:00 to 18:00

hours in the second half of June and July. The other electricity periods were distributed unevenly throughout the studied months, as indicated in Figure 1. The AID established a contract with the electric company defining the amount of power (Kw) that is contracted in each tariff. The amount of power (Kw) that is contracted in the different tariff periods must follow the following conditions: P1≤ P2 ≤ P3≤ P4≤ P5≤P6.

In 2011, the AID was fully irrigated with the new pressurized systems, and hourly records of the irrigation times and irrigation volumes were available. The relationship between the applied water volume (m^3) and time was analyzed in each irrigation management zone and during each tariff period. Additionally, curves of the electricity consumption (KWh) versus time were established for each irrigation management zone and tariff period assuming a homogeneous Energy-Volume ratio (KWh m^{-3}) for each irrigated zone. This ratio was estimated for each irrigated zone from the total energy consumption that was reported in the electricity bills and the total volumes of irrigation water pumped that were obtained from the telemetry system. An ideal scenario with different values of contracted power (Kw) in the AID was analyzed and compared with the current irrigation management in the AID.

Several indicators [energy consumption (KWh), energy cost (€), energy consumption per irrigated area (KWh ha^{-1}), energy cost per irrigated area (€ ha^{-1}), and energy cost per m^3 (€ m^{-3})] were used to characterize the AID energy performance in the 2011 season. The last ratio was calculated by relating the total energy consumption (from the electricity bill) with the total volume that was pumped at each pumping station. These indicators are commonly used in the related literature (Abadía et al., 2008; Moreno et al., 2010; Carrillo-Cobo et al., 2010; Jimenez-Bello et al., 2010).

RESULTS AND DISCUSSION

III.1. The AID evolution

Table 1 presents the general characteristics of the AID before and after the modernization process. According to the 2005-2008 management database of the AID, a total of 610 land owners owning a total of 2,339 plots composed the AID before the modernization. The average plot area before the consolidation process was 1.7 ha, and only 28% of the plots had an area larger than this average value. Approximately 60% of the farms in the district included two or more separate plots. After the land consolidation and modernization processes, the final number of plots in the AID was reduced to 905 with 506 land owners, and the average plot area increased to 4.1 ha. Additionally, the farm size (total area that is owned by a farmer) increased (from 6.7 ha to 7.4 ha on average), and 71% of the farmers own plots that are larger than 5 ha. The irrigation management units are composed of the plots belonging to the farm plus leased plots. Therefore, the irrigation management unit does not necessarily match the farm or plot sizes. The irrigation management unit also increased from 25 ha to 35-40 ha.

The irrigation operation in the pre-modernized AID was the most labor- and time-consuming activity in the agricultural production of field crops. The time and labor costs of irrigation activity drastically reduced with the modernization process, and the farmers can now afford to manage more land. The automation and the reduction of the irrigation labor requirements are perceived by the farmers of the AID as some of the most important outcomes of the modernization process. However, the high energy cost is, at the same time, a major constraint in the new situation.

Although the crop distribution has changed with the modernization process (Table 1), the AID is still characterized by field crops. The major crops before modernization (2005-2008) were alfalfa, winter cereal and maize, representing 45%, 28% and 11% of the total irrigated area, respectively. The modernization process has fostered a very important area under double cropping (52%), generally winter cereals or ray grass followed by a short-cycle maize. In the four irrigation zones in 2011, double cropping occupied the largest area (61% of Artical-Violada, 48% of Abariés, 38% of Colladas and 64% of Matilero).

Table 2 presents the AID's principal crops, its area, the estimated net irrigation requirements and the average applied irrigation doses in the 2011 season and the average irrigation duration and frequency. The AID average seasonal net irrigation requirement (NIR) was 6,180 m^3 $ha^{-1,}$ and the average application dose was 7,082 m^3 ha^{-1} for the 2011 irrigation season. For the pre-modernized situation, from 2006-2008, Barros et al. (2012)

reported an average NIR of 5,438 $m^3\,ha^{-1}$ and an average application dose of 7,362 $m^3\,ha^{-1}$. These results indicate that the intensification of the cropping pattern after the modernization increased the water consumptive use in the AID (by approximately 14 % in 2011). Lecina et al. (2010a) indicated that the irrigation modernization increases the water consumption due to the increase in the crop production (high evapotranspiration), particularly that of field crops, and to the intensification of the cropping pattern. Even with an increase in the water consumptive use of 14% in 2011, the modernization has decreased the average applied irrigation depth by 4%, presumably due to the improvement in the irrigation efficiency of the pressurized systems compared to that of the surface block borders.

The average irrigation time per irrigated block and event (h) and the average irrigation frequency (the time, in days, between consecutive irrigation events) were analyzed during two different periods, from April to June and from July to August, and for the most representative crops (Table 2). The irrigation schedules in the AID are characterized by short and frequent irrigation events. The average irrigation time per event and irrigation block was less than 1.5 hours, and the interval between consecutive irrigations for the period July-August was less than 2 days. The irrigation time per event slightly increased from April-June to July-August, while the irrigation frequency clearly decreased. Similar results were found by Stambouli et al. (2012) for the neighboring Candasnos Irrigation District (CID).

III.2. Irrigation performance in the AID

The SIPI district-wide mean value for the major crops post-modernization in 2011 was 87%. This value is higher than the pre-modernization AID SIPI value of 74 % that was reported by Faci et al. (2000). The 87% SIPI value indicates that, on average, the AID crops were irrigated in the 2011 irrigation season according to the net irrigation requirements, as this SIPI value is close to the 85% potential irrigation efficiency of the sprinkler solid-set systems. The monthly and seasonal values of the SIPI for the major crops during the 2011 irrigation season are presented in Figure 2. The SIPI variability within plots of the same crop was evaluated by the standard deviation (error bars in Figure 2). In general, the highest SIPI variability corresponds to the winter crops (barley and wheat) and could be primarily attributed to the variability of the irrigation management (Salvador et al., 2011). However, these global SIPI values should be handled with great caution due to the large differences between crops and farmers. The seasonal SIPI values for major crops varied from 86% (barley-maize double cropping) to 131% (barley). On a seasonal basis, almost all of the crops were slightly under-irrigated, except for alfalfa, barley and the double-cropping barley-sunflower that were under-irrigated. For the sunflower, the variability within different plots was low (CV of 3%), and for the maize, peas-maize double cropping and peas-sunflower double cropping, the variability was moderate (CV of 20%, 18% and 18%, respectively), indicating that for these crops, the irrigation depth that was applied fluctuated approximately 20% between farmers. The SIPI values for barley, wheat and barley-sunflower double cropping showed the largest variability compared to the other crops. In general, the spatial variabilities of SIPI for double cropping were adequate, except for those of the barley-sunflower combination (117% $\pm$ 86%) that also presented a large variability.

From the beginning of the irrigation season until the end of May, the SIPI values for all of the studied crops, except for maize, wheat and sunflower, were larger than 85%, indicating that the applied irrigation was lower than the NIR (Figure 2.a). The SIPI variability within each crop was generally high (except for maize and sunflower) and could be primarily attributed to the variability in the farmer's irrigation management during this period of low NIRs. This variability decreased in the following months, and the SIPI values of the main crops decreased with time, indicating an increase in the applied irrigation. In August (Figure 2.d), the SIPI values were lower than 100%, and the variability between the plots decreased significantly for most of the crops. The seasonal variability of the SIPI values for the different crops of the AID was significantly lower than that reported by Stambouli et al. (2012) for the neighboring Candasnos irrigation district (CID). The CID is a pressurized irrigation district without energy pumping costs because the water reservoir is located at a high elevation more than 70 m above the irrigated area of the CID where the farmers perform the irrigation scheduling. It is likely that the centralization of the irrigation scheduling from the district office has homogenized the irrigation patterns and has reduced the differences between farmers in the AID.

A farm survey of crop yields performed in the 2011 season in the AID (Jimenez-Aguirre and Isidoro, 2012) provides the average yields of 13,500 kg ha^{-1}, 14,410 kg ha^{-1}, 13,086 kg ha^{-1}, 2,300 kg ha^{-1}, 5,375 kg ha^{-1} and 5,575 kg ha^{-1} for alfalfa, maize (long-cycle), maize (short-cycle), sunflower, barley and wheat, respectively. The yields that were obtained in the AID during the 2011 irrigation season were very similar to those that were obtained in other sprinkler-irrigated areas of the Ebro River Basin (M.A.A.M.A, 2012). Before the modernization, Barros et al. (2012) reported that crop water stress occurred widespread in the AID and that the crop yields were less than optimal. The authors reported the yield data of 12,200 kg ha^{-1}, 10,400 kg ha^{-1}, 4,500 kg ha^{-1}, and 6,600 kg, for alfalfa, maize (long-cycle), barley and wheat for the 2006-2008 period. In general, an important yield increase was observed for maize, a moderate yield increase for barley and alfalfa and a decrease for wheat. Although there is only one year of available data for the post-modernized AID and the comparison between the crop yields before and after modernization should be considered carefully, similar trends have been reported by other authors (Lecina et al., 2010a). Crops such as maize, barley and alfalfa have improved yields with sprinkler irrigation management, reducing the crop water stress periods, as reported in the SIPI analysis. However, wheat irrigation management by sprinkling requires special attention. Wheat is very sensitive to fungal diseases that are promoted by high air humidity (which increases during sprinkler irrigation) and high air temperatures (which are common during the summer). The wheat irrigation management practices should avoid creating adequate ambient conditions for fungal diseases development.

III.3. Solid-set irrigation management in the AID

The irrigation management of the solid-set systems in the AID was analyzed using the telemetry and remote control data. A total of 26,388 hydrant and 136,296 block hydraulic valve irrigation events were analyzed during the 2011 irrigation season (from April to September).

The irrigation scheduling patterns of all of the irrigation events in 2011 in the AID are summarized in Figure 3. The results showed that the frequency (%) of the starting irrigation time increased during the evening hours, reaching a first peak in the early night hours, 19:00–22:00, and a maximum peak at 0:00 (Figure 3.a). In general, the central hours of the day were not chosen to initiate irrigation, as indicated by the minimum frequency values that were obtained between 10:00 and 16:00 hours. Salvador et al. (2011), for the neighboring sprinkler Candasnos Irrigation District (CID) without electricity pumping costs, reported two periods of high frequency for the starting time of the irrigation events, approximately 08:00 h (24%) and approximately 20:00 h (30%). The large differences in the timing of irrigation between the AID and CID were mainly due to the variable electricity tariff during the day in the AID and the lack of electricity costs in the CID. The starting time of the irrigation events in the AID was at night. As a conclusion, the higher electricity costs during the daylight hours and the centralized irrigation management are very effective in forcing nighttime irrigation, thereby decreasing the wind drift and evaporation losses by sprinkling at night hours with a lower wind speed. Khadra and Lamaddalena (2010), in Bari (southern Italy), also reported a peak irrigation water use during the central hours of the day (from 9:00 to 17:00). In their study, the irrigation system was drip irrigation in olive trees and vegetable crops. The differences between both of the irrigation systems explained the opposite irrigation timing that was found in their study and in the AID, as the drip irrigation performance is largely independent of meteorology and has a lower energy demand.

Normally the irrigation blocks (IBs) composing a plot are sequentially irrigated during an irrigation event. When the IB sequence, the starting irrigation time and the irrigation duration remain constant, each IB consistently irrigates at the same time of the day and presumably with homogeneous meteorological conditions. This irrigation pattern promotes differences in the water application depth in the IBs of the same plot as the irrigations in one particular block are repeated during every irrigation event. The wind speed and the air relative humidity in the Ebro Valley present a clear pattern of variability throughout the day (Martinez-Cob et al., 2010), with a high wind speed and evaporative demand during the central hours of the day and a low wind speed and evaporative demand at night. Other authors working in the Ebro River basin (Dechmi et al, 2004; Martinez-Cob et al. 2010; Sánchez et al., 2011) reported the benefit of varying the irrigation timing of the different blocks of sprinkler irrigated plots throughout the season. Ways to change the block irrigation timing include changing its IB irrigation sequence or changing the starting time of the irrigation events to different dates. Figure 3.b presents the frequency of changes in the IB sequences of the plots in 2011. A total of 77% of the plots do not change their IB sequence throughout the season (constant sequence), while 23% of the plots do. Figure 3.c presents, for the plots that maintain a constant IB sequence, the percentage of irrigation plots that do not change their irrigation starting time throughout the season. The analysis showed that the irrigation starting time was conserved in 38%, 44% and 41% of the plots in April, May and the first half of June, respectively. From the second half of June until the end of August (the period with large irrigation water requirements), most of the plots changed their irrigation starting time. The analyzed months with the lowest irrigation requirements (April, May and the first half of June) presented the most constant irrigation scheduling pattern. A major intervention of the irrigation manager on the plot irrigation scheduling could avoid the adverse effects of this irrigation pattern.

The wind speed has often been documented as the most significant meteorological variable affecting the wind drift and evaporation losses (WDEL) and the irrigation uniformity of the sprinkler systems (Playán et al., 2005; Zapata et al, 2009; Sanchez et al., 2010). Significant water losses and the lack of irrigation uniformity occur during sprinkler irrigation, particularly in areas with strong winds and a high evaporative demand (Playán et al., 2005). In arid areas, farmers sometimes stop irrigation in response to strong winds or precipitation events. To know if these practices are applied in the AID, the evolution of the daily values of applied irrigation volume in the AID, the wind speed and the precipitation level are presented in Figure 4. High volumes of irrigation water were observed during the weekends (sharp peaks in Figure 4) independent of the meteorological conditions. The main reason for these peaks is the low electricity costs for agricultural use on Saturdays and Sundays

(P6 electric tariff). Additionally, a slight decrease in the irrigation volume was observed before and after medium-to-large precipitation events, but no effect on the wind speed was visible in Figure 4.

III.4. Analysis of the adequacy of the power contracted during each energy tariff period

The total electricity bill of an irrigation district includes the power (Kw) cost and the energy (Kwh) cost. The cost values are expressed in euros (€; 1 euro = 1.31 US dollar). The energy cost depends on the pumped water volume, the pressure and the timing of the pumping (time distribution). The power cost exclusively depends on the amount of Kw that is contracted in each tariff and, when exceeding the contracted values, the surpass penalties. The district manager decides annually, at the beginning of the irrigation season, the power (Kw) that is contracted in each tariff. This important economic decision has many uncertainties as the district manager does not know the irrigation requirements of the AID for that season because they depend on the cropping pattern, which also depends on the water availability in the reservoirs and on the agricultural costs.

To minimize the electricity bill of an irrigation district, it is important to maintain a high irrigation efficiency and to optimize the pumping operation. Irrigation should occur during the low-cost energy periods, and the optimum power should be contracted at each tariff period. The adjustment of the contracted Kw to the consumed Kw during each tariff period prevents the payment of unused power (over-contracting) and avoids the penalization cost due to surpassing the contracted power (under-contracting).

Figure 5.a presents the monthly distribution of the irrigation time (in percentage) of each electricity tariff period throughout 2011 in the AID. In all of the studied months, most of the irrigation time was performed during the P6 tariff period (from 77% in April to 100% in August). Approximately 23% of the irrigation time in April and May take place during the P5 tariff period (the second cheapest period). During the second half of June and all of July, the available time of the cheapest period (from 00:00 to 08:00 h) was not enough to satisfy the crop irrigation requirements, and part of the irrigation was performed during the other available tariff periods (P2 and P1, Figure 5.a). A total of 17% and 14% of the monthly irrigation time during the second half of June and July, respectively, were performed during the P2 tariff period. A very low proportion of the irrigation time was performed during the P4, P3 and P1 tariff periods.

Figure 5.b presents the monthly irrigation volume that was applied during each electricity tariff period throughout 2011 in the AID. The largest irrigation volumes that were applied correspond to the months with the highest irrigation requirements, July and August, and the

distribution of the volumes between the electricity tariff periods is clearly oriented to the cheapest one (P6). During the second half of June and all of July, part of the applied irrigation was performed during the second most expensive energy period (P2).

Table 3 presents for each irrigated zone of the AID the irrigated area, the number of hydrants, the percentage of shared hydrants, the average number of irrigated blocks per hydrant and the established pumping head. The largest zone was Artical-Violada (1,628 ha), followed by Abariés (1,320 ha); Colladas and Matilero were the smallest and similar in size (approximately 400 ha). The percentage of hydrants that are shared by two or more farmers was low in the Colladas and Matilero irrigated zones (10% and 13% of the hydrants, respectively) and increased to 29% in the large irrigated zones of Abariés and Artical-Violada. Zapata et al. (2009) reported that for the manual irrigation scheduling, the shared hydrants represent an additional constraint for water management. The largest pressure head (79 m) in the pumping station corresponded to the Abariés zone. The other irrigated zones required a similar pumping head (72 m). Table 3 also presents, for each irrigated zone, the average ratio of energy consumption versus the volume of pumped irrigation water. The total energy consumption of the AID during the 2011 irrigation season was 6,057 MWh, and the total volume pumped was 21.47 $10^6 m^3$. The average ratio for the entire AID was 282 KWh per 1000 m^3 of pumped water. For each irrigated zone, the ratio was considered constant for the whole season, although its value varied with time depending on the system status (number of operating hydrants, distances and elevation between the pump and the open hydrants and pump efficiency). The ratio also varied between the irrigated zones due to differences in the required pumping head and pumping efficiency. The Matilero irrigated zone presents a significantly higher ratio (309 KWh per 1000 m^{-3}) than Colladas (264 KWh per 1000 m^{-3}) with an equal required pumping head. This high ratio is indicative of a lower pumping efficiency that should be revised. The ratios have been used to transform the volumes of applied irrigation to energy consumption for each irrigated zone.

The adequacy of the electrical contracted power (Kw) during each tariff period related to the energy consumption (KWh) in the AID was analyzed. The evolution of the maximum and average hourly values of energy consumption (Kwh) over 24 hours during different days of the week was analyzed independently in the four irrigated zones of the AID for every month of the irrigation season. Figure 6 presents the maximum hourly values of energy consumption (Kwh) in the month of July for the zones of Artical-Violada (Figure 6.a), Abariés (Figure 6.b), Matilero (Figure 6.c) and Colladas (Figure 6.d). The dashed line presents the contracted power (Kw) during each energy tariff period in 2011. During every weekend (Saturday and Sunday), the cheapest energy tariff period (P6) operated for the entire day. The results show that, in general, the maximum values of energy consumption did not exceed the power that was contracted, except in the P1 period (central hours of the day), especially in the Artical-Violada (Tuesdays and Fridays), Colladas (Fridays) and Matilero (Mondays, Tuesdays and Thursdays) zones. In this last zone, the higher values of the maximum energy consumption only occurred at the beginning of the P1 period between 11:00 and 12:00 hours. The results also indicate that the actual power (Kw) that was contracted in some of the energy tariff periods was over-dimensioned in 2011. This excess in the power that was contracted was especially important for the P2 energy tariff period in the four zones of the AID and for the P6 tariff period in the Abariés and Colladas zones. The intensive irrigation during day and night on the weekends caused a considerable decrease in the water consumption during the early Monday hours compared with that of the other weekdays. The average values of the hourly energy consumption in August are presented in the four zones of the AID (Figure 7). In this month, the cheapest energy tariff period, P6, operates continuously; therefore, the energy cost of day and night irrigation is the same. However, the energy consumption during the central hours on weekdays decreased significantly. This behavior was not detected during the weekend, when the hourly energy consumption is homogeneous during the day and night hours. The reduction in irrigation during the central weekday hours can be attributed to the influence of adverse meteorology (largest wind drift and evaporation losses during this period) on the irrigation performance, but this effect is not observed on the weekends. It is likely that the routine that was established in the previous months with high tariff periods or the significant number of part-time farmers that like to check irrigation during the weekends can explain the irrigation patterns of August.

An economic analysis of the contracted power (Kw) during the different tariff periods and the electricity cost (€) in 2011 and in a proposed scenario for the four irrigation zones of the AID is presented in Table 4. The same volume of pumped water in the 2011 irrigation season was assumed for the proposed scenario. The changes in the scenario that was proposed to optimize the electricity bill included, for the whole AID, an increase in the contracted power during the tariff period P1 from 100 to 165 KW year^{-1}, a reduction during the tariff periods P2 to P5 from 3951 to 2300 KW year^{-1} and the maintenance of the power during the tariff period P6 at 4823 KW year^{-1}. The total electricity cost for the AID in 2011 under the current electricity contract was 466,754 €. The power cost, including penalties, represented 26.5% of the total electricity cost, ranging between 24.7% for the Matilero zone and 30.5% for the Colladas zone. In the proposed scenario, these values were reduced to an average of 19.7% of the total electricity cost, ranging from 17.6% for the Abariés zone to

23% for Colladas zone. The total electricity cost of the proposed scenario was 427,481 €, representing a decrease of 8.4% in the total electricity cost.

The average electricity cost per unit of volume that was pumped in the AID in 2011 was 21.7 € per 1000 m^{-3}. The highest cost occurred in the Matilero zone, with 26.6 € per 1000 m^{-3}.

The differences between the irrigated zones were also observed in the proposed scenario, as only the changes in the contracted power were considered. The important differences between the Matilero and the other irrigated zones should be analyzed because all of the irrigated zones are quite similar in crop patterns and pumping heads, and this difference was not expected.

The analysis of the volumes of applied irrigation water during each tariff period using the telemetry records of past seasons can be an important tool in overcoming the uncertainty regarding the amount of power to be contracted in the next season. Annually, without knowing the crop pattern, the AID manager must decide how much power to contract during any tariff period. The analyses and results that are presented in this study can be a valuable decision-making tool for managers of water user associations. The analysis should be performed in successive seasons to provide consistent results.

CONCLUSIONS

Irrigation modernization has greatly changed the land structure (tenure and management units) in the AID. The possibilities of the pressurized irrigation systems and the need to amortize them have promoted large areas of crops with higher economic margins or double cropping that, in general, have increased the amount of water that is used by the crops. Additionally, the new irrigation systems have improved the irrigation efficiency and have decreased the average irrigation depth applied to the crops. The comparison should be considered carefully, as there is only one year of post-modernized data. Additionally, the average SIPI index changed from 74% for the pre-modernized district to 87% for the post-modernized district, indicating better water management in the modernized AID, with a higher water productivity and lower irrigation return flow in the drainage system.

The spatial variability of the SIPI index at the beginning of the irrigation season was generally high (except for maize and sunflower) and could be attributed to the variability in farmers' irrigation management during this period of low NIRs. This variability decreased in the following months, and during July and August, the variability was very low for most of the crops. The central and remote management of the irrigation demands homogenize the irrigation patterns. The analysis of the temporal variation of the SIPI index was adequate in assessing the on-farm irrigation performance. However, the SIPI does not really measure the irrigation efficiency as the net irrigation requirements, instead of the actual crop consumptive use, are used. This constraint is a major limitation when comparing the crop SIPI under different management schemes or irrigation systems as the crop evapotranspiration is likely to change with crop water stress.

A strong influence of the different costs of the electricity tariff periods on the irrigation scheduling was observed. In all of the studied months (April to September), most of the irrigation events were applied during the cheapest energy period, P6, (from 77% in April to 100% in August). In July and the second half of June (the period with the largest crop water requirements and very few periods of low energy costs), part of the irrigation events had to be applied during the second most expensive energy period (P2).

The pattern of energy demand on weekdays showed that the intensive irrigation during the weekend was followed by a low energy demand in the early Monday hours. An increase in the energy demand was observed on Thursdays. This pattern was observed in all of the irrigated zones of the AID, indicating that the farmers are mostly part-time agriculturalists. A more homogeneous distribution of irrigation throughout the week could somewhat decrease the energy cost. The effect of meteorology on the irrigation management in the AID was very limited as the irrigation scheduling was centralized. The relationships in the AID between the daily values of pumped water and the precipitation and average wind speed were less significant than those of the other similar sprinkler irrigation districts in the Ebro River basin.

The irrigation management in the AID is a combination of farmer demands and manager intervention. A large number of irrigation events (30%) in the AID begin at midnight. A large number (77.4%) of the plot irrigation events that were analyzed used a constant IB sequence and a constant starting irrigation time. These irrigation patterns promote water and crop yield variability between IBs of the same plot. Generally, the irrigation pattern in the AID was characterized by short (approximately 1.5 hours per IB and event) and frequent (almost daily between July and August) irrigation events. In general, adequate irrigation practices were observed in the AID, with the irrigation occurring at nighttime to reduce wind drift and evaporation losses and during the lower tariff periods (nighttime and weekends) to reduce the electricity cost. However, some areas for improvement were also identified, such as the need to periodically change the irrigation starting time of the IBs composing a plot or the IB irrigation sequence to reduce the water and yield variability.

In August, with the cheapest tariff period P6 during the entire month, irrigation during the central hours of the weekdays decreased significantly. This reduction in the weekday water application can be beneficial due to the largest wind drift and evaporation losses during this period of the day. However, the weekend water application was maintained throughout the day. This behavior can be explained by the routine that was established in previous months or by many farmers in the AID practicing agriculture part-time, preferring to have their irrigation in operation during the weekend to check their systems.

The analysis of the telemetry data records has raised some aspects that should be incorporated into the water and electricity management routines of the irrigation districts. One aspect is the need to know the crop distribution pattern and crop irrigation requirements as early as possible, and a second is the need to adjust the contracted power related to the power demand. Annually, even without knowing the crop pattern, the AID manager faces the decision of how much power to contract during the different tariff periods. A methodology for analyzing the adequacy of the contracted power during each tariff period in relation to the power demand throughout the irrigation seasons could be a valuable tool for the district manager in optimizing the electricity cost of the AID. A proposed scenario, based on adjusting the contracted power to the average consumption, resulted in a decrease of 8.4% in the total electricity cost.

III. Acknowledgements

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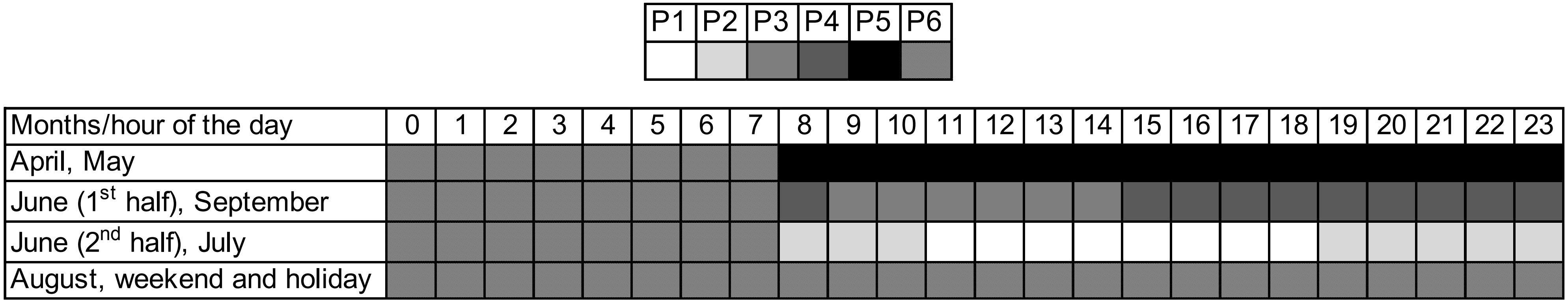

Figure 1. Hourly distribution of the six tariffs during the different months of the irrigation season (April to September) of the electric companies for the irrigation pumping stations.

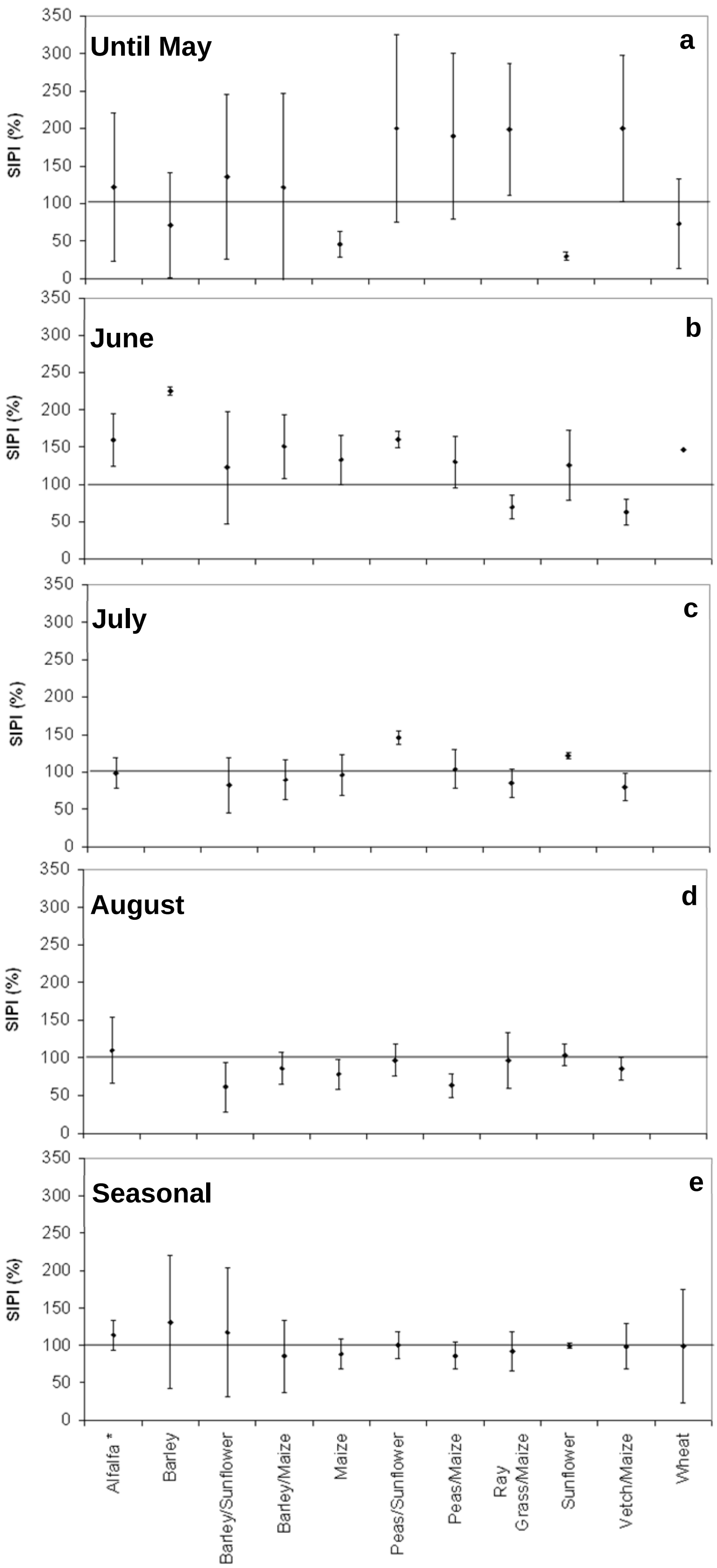

Figure 2. Average values of monthly (a, b, c and d) and seasonal (e) irrigation performance index (SIPI) values for the major crops during the 2011 irrigation season. The error bars indicate ± standard deviation.

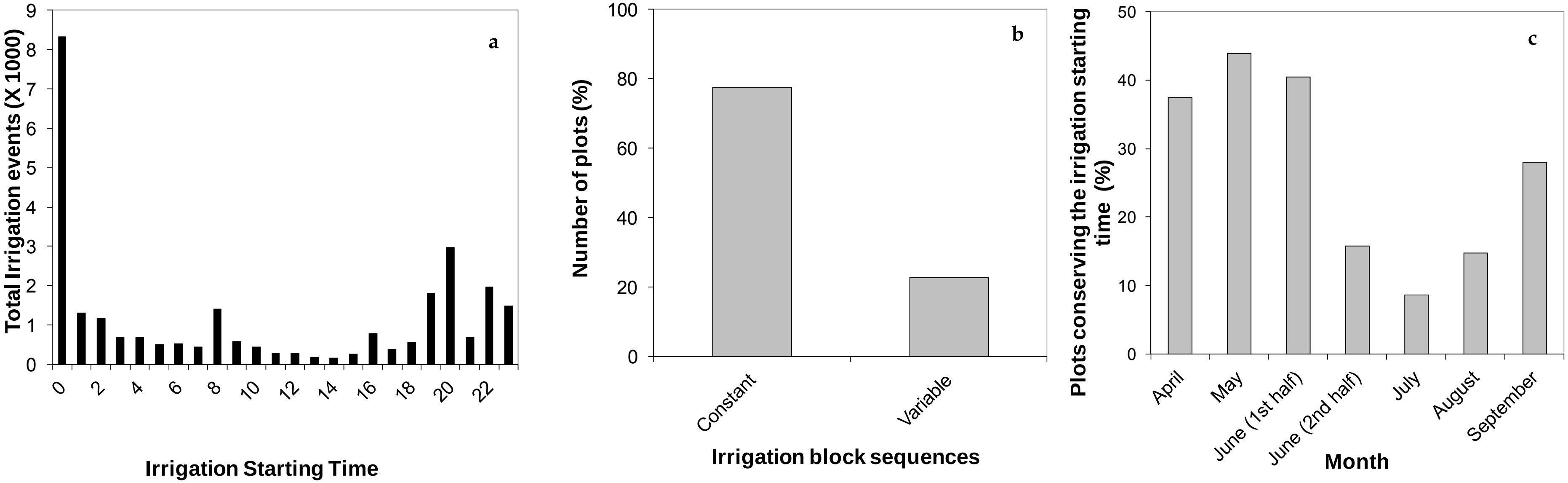

Figure 3. Histogram of the starting irrigation time (hour of the day) for all of the hydrant irrigation events during the 2011 irrigation season in the Almudévar Irrigation District (AID) (a). Number of plots, expressed in percent of the total, that maintained a constant or variable irrigation block sequence throughout the 2011 season in the AID (b). Number of plots that maintained both a constant irrigation block sequence and irrigation starting time, expressed in percent of the total, during the 2011 irrigation season in the AID (April-September) (c).

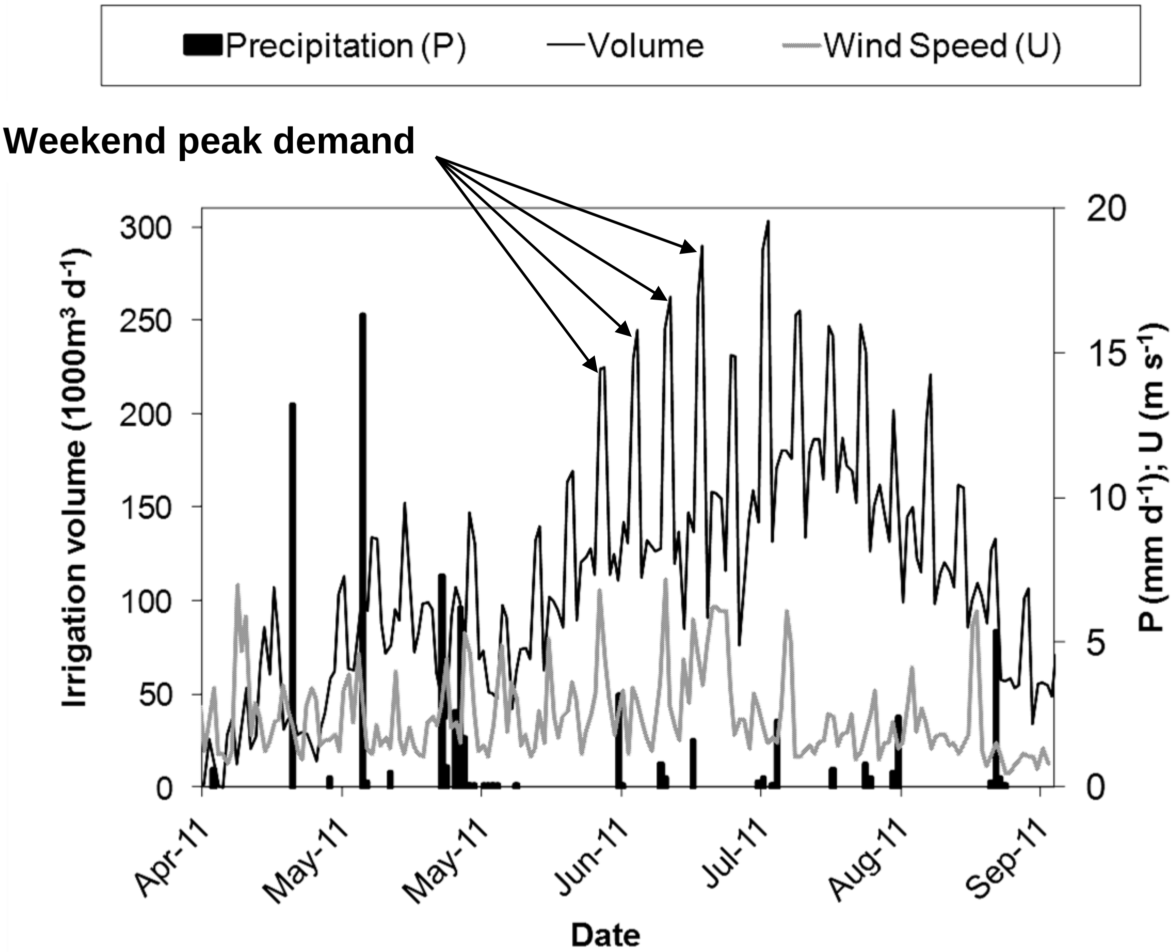

Figure 4. Daily evolution of applied irrigation volume (1000 m^3 d^{-1}), average wind speed (m s^{-1}) and precipitation (mm d^{-1}) in the Almudévar Irrigation District (AID).

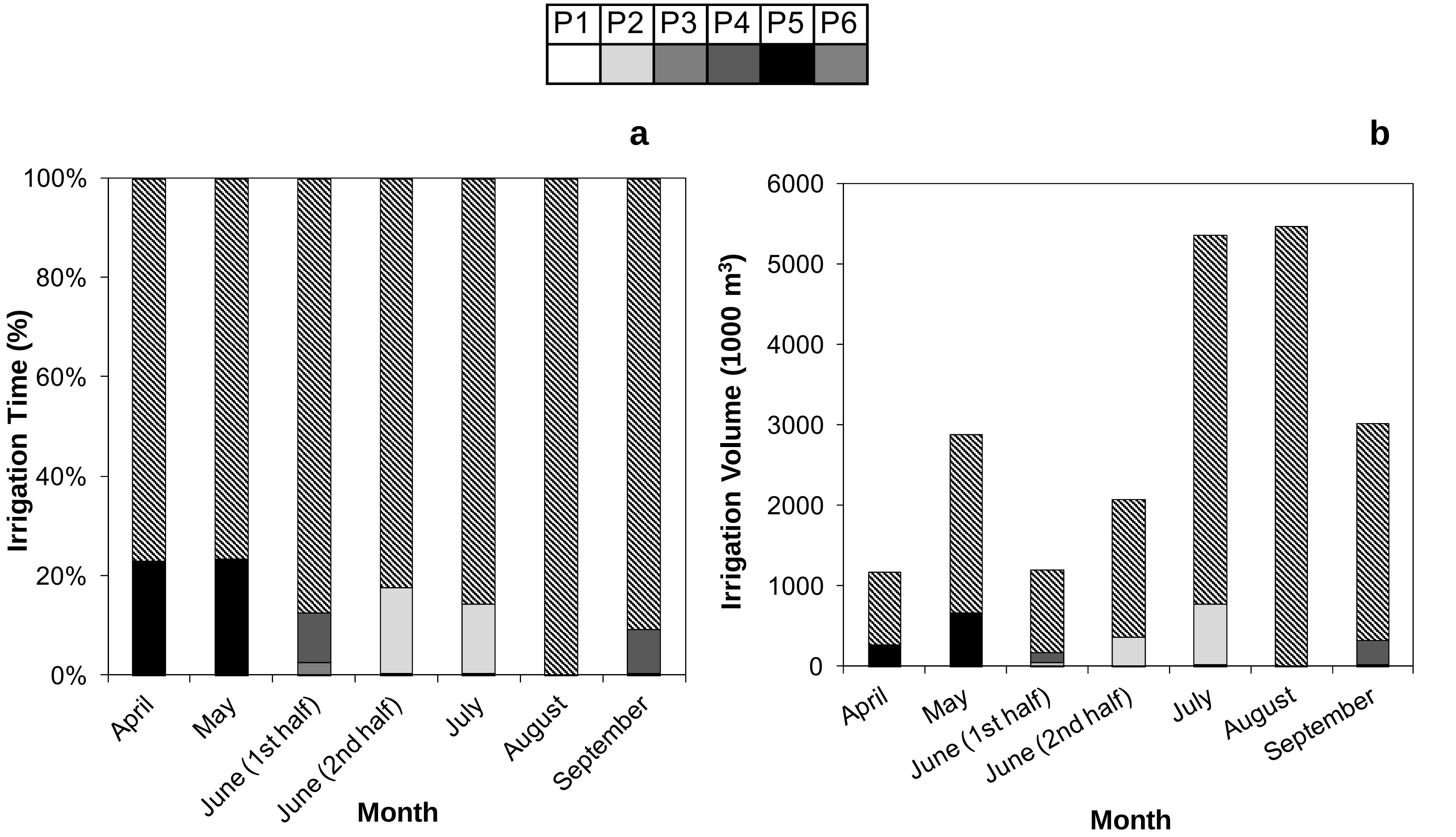

Figure 5. (a) Monthly irrigation time (%) performed during each of the six electricity tariff periods in the Almudévar Irrigation District (AID). (b) Monthly distribution of the pumped water volume (x 1000 m^3) in each of the six electricity tariff periods in the AID.

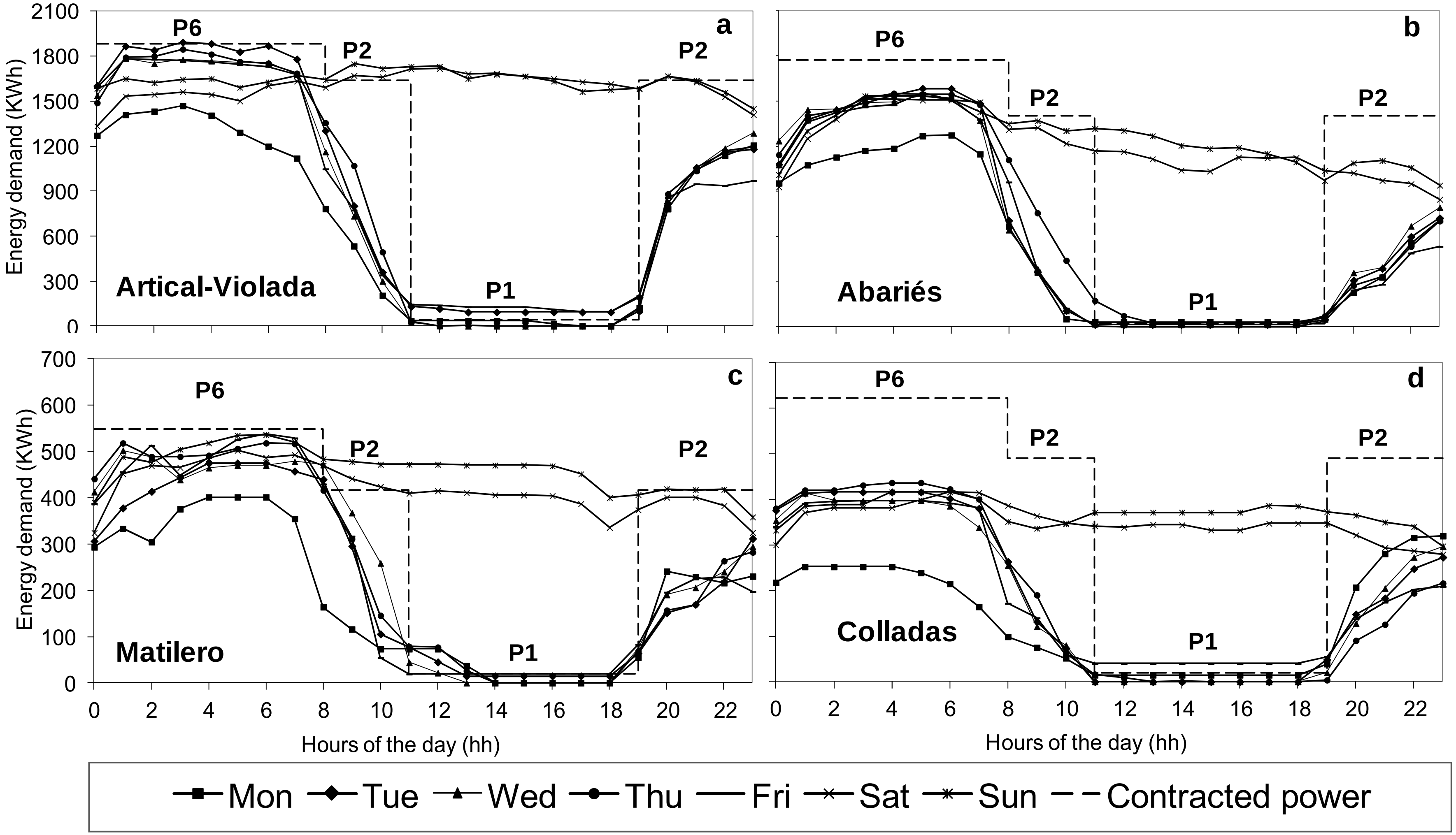

Figure 6. Maximum energy consumption (Kwh) for each day of the week in July in the four irrigation zones of Artical-Violada (a), Abariés (b), Matilero (c) and Colladas (d) of the Almudévar Irrigation District (AID). The dashed line represents the contracted power (Kw) during each electricity tariff period.

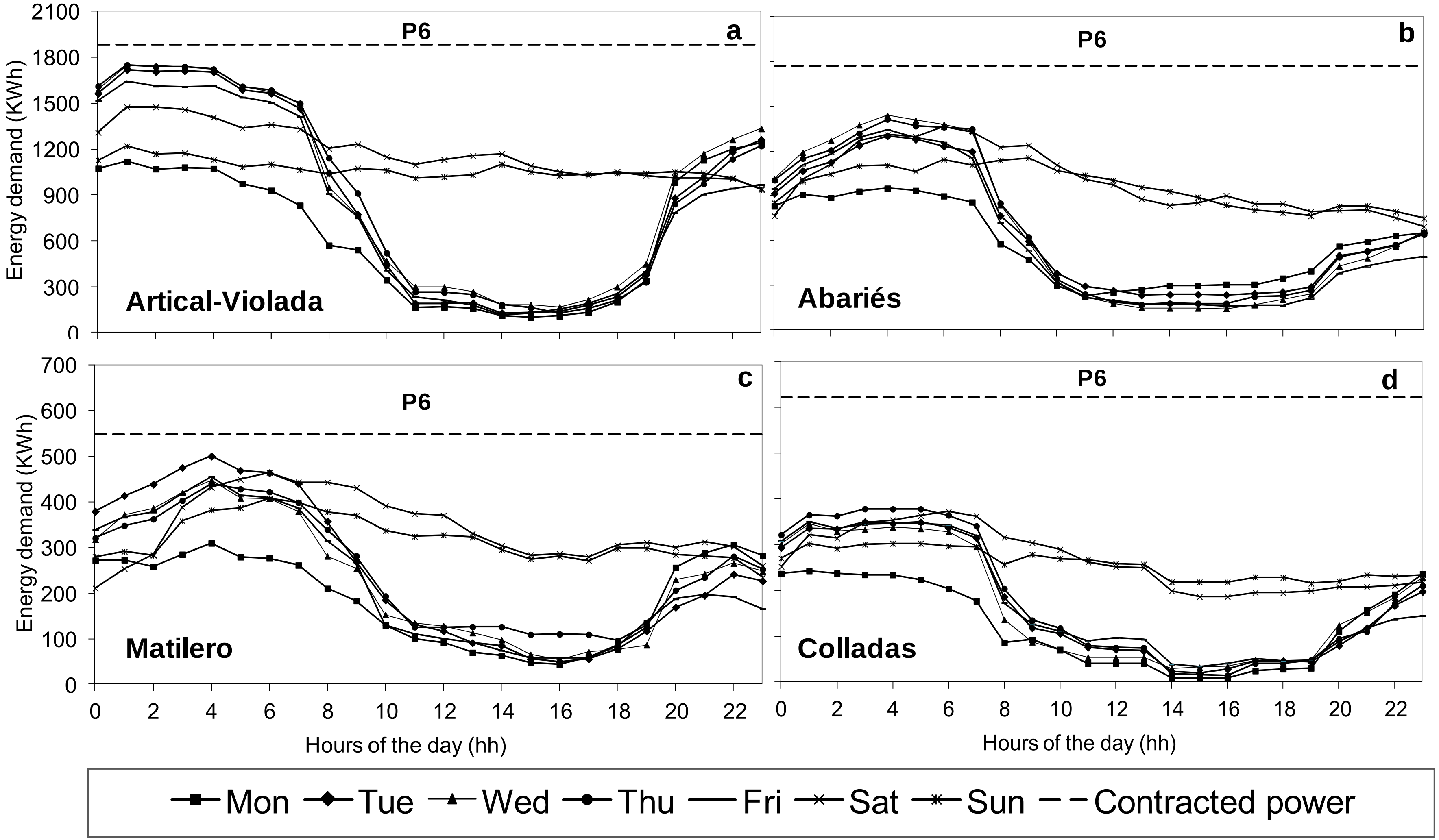

Figure 7. Average energy consumption (KWh) for each day of the week in August in the four irrigation zones of Artical-Violada (a), Abariés (b), Matilero (c) and Colladas (d) of the Almudévar Irrigation District (AID). The dashed line represents the contracted power (Kw) during the electricity tariff period P6.

Table 1. General characteristics of the Almudévar Irrigation District before and after irrigation modernization.

AID characteristics	Before Modernization (2006 to 2008)	After Modernization (2011)
Total area (ha)	4,087	3,744
Number of farmers	610	506
Number of plots	2,339	905
Average area of the plots (ha)	1.7	4.1
Average farm size (ha)	6.7	7.4
Number of plots per farm	3.8	1.8
Average irrigation management unit size (ha)	25	35-40
Major Crops	Alfalfa (45%); Winter Cereal (28%); Maize (11%)	Double Cropping (52%); Maize* (18%); Alfalfa (14%); Winter Cereal (10%)

** This value did not account for the maize as a double crop*

Table 2. Area (ha) of the major crops, seasonal net irrigation requirements (NIRs, $m^3 ha^{-1}$), seasonal irrigation dose ($m^3 ha^{-1}$), irrigation time (h IB^{-1} $event^{-1}$) and irrigation frequency (days) during two periods in the Almudévar Irrigation District during the 2011 irrigation season. The values in parentheses indicate the percent coefficient of variation.

Crop	Area		Net Irrigation Requirements ($m^3 ha^{-1}$)	Irrigation Dose ($m^3 ha^{-1}$)	Irrigation Time (h IB^{-1} $event^{-1}$)		Irrigation Frequency (d)	
	ha	%			to June	July-Aug.	to June	July-Aug.
Alfalfa	419.1	13.9	9,380	8,796 (20)	1.39	1.49	1.79	1.55
Barley	295	9.8	1,419	1,085 (89)	1.40	-	20.15	-
Maize	563	18.7	7,295	8,253 (20)	1.09	1.40	2.22	1.16
Barley/Maize	302.3	10.0	6,696	7,818 (48)	1.06	1.34	2.80	1.35
Ray Grass/Maize	201.5	6.7	8,162	8,863 (26)	1.09	1.39	1.82	1.27
Peas/Maize	36.9	1.2	8,876	10,298 (18)				
Vetch/Maize	420.1	13.9	8,260	8,371 (30)	1.06	1.55	1.50	1.25
Sunflower	26.9	0.9	6,524	6,558 (03)				
Wheat	171.2	5.7	2,173	2,196 (76)				
Other Double Cropping	318.3	10.6	6,624	6,175 (48)				
Barley/Alfalfa	172.1	5.7	2,572	2,450(65)				
Barley/Sunflower	89.6	3.0	3,880	3,342 (86)				

Table 3. General characteristics of the four irrigated zones in the Almudévar Irrigation District (AID).

Irrigated zone	Irrigated area (ha)	Number of hydrants	Shared hydrants (%)	Average number of blocks per hydrant	Pumping pressure head (m)	Ratio energy/volume (KWh 1000 m^{-3})
Abariés	1,320	109	29	6.8	79	288
Artical-Violada	1,628	122	29.5	7.6	68-72	276
Colladas	405	29	10	7.4	72	264
Matilero	391	31	13	7.4	72	309
Total	3,744	291	25.5	7.3	71.3	282

Table 4. Electricity cost analysis for the pumping stations of the four irrigated zones of the Almudévar Irrigation District for the current situation and for a proposed scenario with new values of the contracted power during each tariff period. The power cost, penalty cost for exceeding the contracted power, total power cost, total electricity cost and average electricity cost per unit of pumped water are presented for the current situation and proposed scenario.

Scenario	**Irrigated zone**	**Contracted power during each tariff period (KW year^{-1})**						**Power cost (€)**	**Penalties by power exceeded (€)**	**Total power cost (€)**	**Total electricity cost (€)**	**Electricity cost (€ 1000 m^{-3})**
		P1	**P2**	**P3**	**P4**	**P5**	**P6**					
Current	Abariés	20	1,402	1,402	1,402	1,402	1,770	42,443	470	42,914	154,836	20.8
	Artical-Violada	40	1,642	1,642	1,642	1,642	1,882	49,455	2,294	51,749	206,913	21.6
	Colladas	20	491	491	491	491	623	15,089	226	15,314	50,118	21.3
	Matilero	20	416	416	416	416	548	12,890	661	13,551	54,887	26.6
	Total	100	3,951	3,951	3,951	3,951	4,823	119,877	3,651	123,528	466,754	**21.7**
Proposed	Abariés	30	600	600	600	600	1,770	21,327	2,653	23,981	135,874	18.2
	Artical-Violada	75	1,100	1,100	1,100	1,100	1,882	35,653	3,064	38,717	194,521	20.3
	Colladas	30	300	300	300	300	623	10,186	148	10,335	44,845	19.1
	Matilero	30	300	300	300	300	548	9,978	1,122	11,100	52,241	25.3
	Total	165	2,300	2,300	2,300	2,300	4,823	77,145	6,988	84,132	427,481	**19.9**