SOLID-SET SPRINKLER IRRIGATION CONTROLLERS DRIVEN BY SIMULATION MODELS: OPPORTUNITIES AND BOTTLENECKS

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ABSTRACT

Farmers continue to show wide differences in irrigation water use, even for a given location and crop. Irrigation advisory services have narrowed the gap between scientific knowledge and on-farm scheduling, but their success seems to have been limited. Sprinkler irrigation performance is greatly affected by meteors such as wind speed, whose short-time variability requires tactical adjustments of the irrigation schedule. Mounting energy costs often require consideration of inter- and intraday tariff evolution. Opportunities have arisen which permit to address these challenges through irrigation controllers guided by irrigation and crop simulation models. Remote control systems are often installed in collective pressurized irrigation networks. Agrometeorological information networks are available in regions worldwide. Water Users Associations use specialized databases for water management. Different configurations of irrigation controllers based on simulation models can develop, continuously update and execute irrigation schedules aiming at maximizing irrigation adequacy and water productivity. Bottlenecks requiring action in the fields of research, development and innovation are analyzed with the goal of establishing agendas leading to implementation and commercial deployment of advanced controllers for solid-set irrigation.

CE Database subject headings: sprinkler irrigation; control; models; irrigation systems; irrigation districts

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INTRODUCTION

Economic development and a growing world population are increasing global demand for agricultural products. Alexandratos and Bruinsma (2012) predicted that world food demand will increase by 60% by 2050. According to the International Energy Agency (IEA), the use of biofuels could grow more than fourfold from 2008 to 2035 (IEA, 2012). Irrigated agriculture accounts for 40% of global food production (World Water Assessment Programme, 2009). The world irrigated area amounts to 302 M ha and occupies 16% of the total arable land (Alexandratos and Bruinsma, 2012). By the beginning of the 21st century, pressurized irrigation systems only accounted for 12% of the total irrigated area (FAO, 1998-2002). About 60% of the world irrigated area should be modernized in order to match the future world demand for food and biofuel production (Alexandratos and Bruinsma, 2012). Additionally, the effective irrigated area should be extended by 15% for the same aim. These changes will mainly take place in developing countries. Pressurized irrigation systems are commonly adopted for modernization purposes and new irrigated areas. The area irrigated by sprinkler and drip systems has increased from 37% to 60% since 1979 in the United States (USDC, 1986; USDA, 2009). For instance, in Spain pressurized irrigation systems have increased from 19% to 70% in the last 30 years (MAPA, 1985; MAGRAMA, 2011). Solid-set sprinkler irrigation systems have experienced wide diffusion in countries such as Brazil (1.57 M ha, 35.3% of the irrigated land) or Spain (0.48 M ha, 14% of the irrigated land).

Despite irrigation modernization, water withdrawn by irrigated agriculture is forecasted to increase by 11% in 2030 (World Water Assessment Programme, 2009). Water availability will be a major constraint to balance supply and demand for agricultural products in the coming decades. Moreover, oil energy prices and electricity prices are predicted to increase by about 25% and 15%, respectively, in 2035 (IEA, 2012), raising the irrigation costs for pressurized systems requiring pumping stations. These perspectives encourage farmers to invest in water-efficient technologies aiming at maximizing economic return from their investments in irrigation systems.

At the on-farm level, water use remains unsatisfactory. Salvador et al. (2011) analyzed seasonal irrigation water application patterns in 1,627 plots located in large irrigation projects of the Ebro valley of north eastern Spain. Irrigation adequacy was assessed using the ARIS (Annual Relative Irrigation Supply) indicator proposed by Malano and

Burton (2001). This indicator can be determined as the ratio of irrigation water application (m^3 ha^{-1} yr^{-1}) to net irrigation requirements (m^3 ha^{-1} yr^{-1}). Salvador et al. (2011) found average ARIS values of 1.41 for surface irrigation, 1.16 for sprinkler irrigation and 0.65 for drip irrigation. Inter plot deviation from these average values was surprisingly large. For instance, in the case of solid-set irrigated corn (a drought-sensitive crop) the average ARIS was 1.20 and its standard deviation was 0.30. Lorite et al. (2004) reported similar results in the context of Andalusia, southern Spain. These findings call for a generalized improvement of irrigation scheduling, adjusting water application to crop water requirements and reducing the variability introduced by the human factor. In these days of information technologies, advanced, self-programming irrigation controllers can contribute to this problem, enhancing water productivity in pressurized irrigation regardless of the irrigators' skills. Such irrigation controllers are currently being developed to suit the needs of different pressurized irrigation systems.

Controllers for urban landscape irrigation

The development of irrigation controllers for urban landscapes is nowadays progressing in two paths: exploiting evapotranspiration information and using local soil water sensors (Cárdenas-Lailhacar and Dukes, 2012; Grabow et al., 2013). Urban landscape water requirements can be determined from weather conditions, type of landscape, and site conditions. Evapotranspiration can be obtained from historical databases (recorded in the controller), from an adjacent weather station or through web server broadcasts. Different studies have compared evapotranspiration controllers, soil water controllers and irrigators. Davis et al. (2009) found that evapotranspiration controllers could save 43%, of the water when compared with manually operated time controllers. McCready et al. (2009) showed water savings of between 11 and 75% when comparing evapotranspiration with soil water based controllers and manually operated time controllers, respectively. Grabow et al. (2013) reported best adequacy and efficiency with soil water controllers. Dobbs et al. (2013) presented an educational interactive simulation model designed to evaluate and improve advanced controllers and manual irrigation practices.

Controllers for greenhouse irrigation automation

Protected agriculture is expanding in many parts of the world, particularly in marginal agricultural land. Input productivity, particularly water, can be higher in greenhouses than in conventional agriculture. As an example, in Spain only 1.7% of the total irrigated area is under greenhouses (62,500 ha), and only 2,500 ha of greenhouses are equipped with high technology systems (MARM, 2011). Controllers in greenhouses are used for a number of purposes, including irrigation scheduling. Computer-based monitoring systems using a variety of sensors (for the estimation of water requirements or for nutrient and carbon dioxide consumption) are commercially used in greenhouses. Intelligent, autonomous systems monitoring and controlling greenhouse operations (climate control), specific processes (transplanting), or more complex activities (correcting plant nutritional unbalances) continue to be developed and applied in greenhouse systems (Stanghellini and Montero, 2010). The benefits of greenhouse automatic control (product yield, quality and precocity) have been reported to balance the cost of the control equipment in different productive orientations.

Controllers for drip irrigated orchards

Regulated deficit irrigation (RDI) is based on the fact that plant sensitivity to water stress varies among phenological stages. As a consequence, water stress at specific periods of vegetative growth can help control growth and vegetative-fruit competition (Chalmers et al. 1981). In the last thirty years, RDI techniques have received relevant interest in the literature as tools to achieve significant reductions in irrigation water use. Fereres and Soriano (2007) reported that RDI has enjoyed more success in tree crops and vines than in field crops. Solutions for automatic controllers to irrigate orchards under RDI techniques are often based on continuous monitoring of plant or soil water status (Intringliolo and Castel, 2005). Reducing data acquisition and processing requirements, and cutting off the required knowledge and skills are critical to future expansion of RDI techniques.

Controllers for self-propelled sprinkler irrigation machines

Self-propelled sprinkler irrigation machines have experienced worldwide success because of their advantages relative to other irrigation systems such as: 1) high potential for uniform and efficient water applications; 2) high degree of automation, allowing precision farming, such as variable rate technology; and 3) ability to apply water and nutrients over a wide range of soil, crop and topographic conditions. In the USA more than 47% of the irrigated land (10.5 M ha) is irrigated by center-pivots and linear-move sprinkler systems (USDA-NASS, 2009). In Brazil these systems occupy 20% of the irrigated area (0.85 M ha). In Spain, self-propelled sprinkler irrigation machines cover 8% of the total irrigated area (0.26 M ha) (MARM, 2011). The large fields typically irrigated with self-propelled sprinkler machines often evidence relevant soil variability (infiltration rate, soil water holding capacity, topography, or soil chemical properties). One of the most important constraints to productivity-oriented management lies in adapting input application to field variability (Evans and King, 2012). Precision agricultural technologies, such variable-rate irrigation, fertilizer, seeding, and pest control have been developed for sprinkler irrigation machines. Their potential benefits have been contrasted by several authors (Sadler et al., 2005; O´Shaughnessy and Evett, 2010). The balance between benefits of precision agriculture and the cost of implementing such technology has not been firmly established, as this technology is still in intense progress (El Nahry et al., 2011).

Developments in solid-set irrigation controllers

Solid-sets, the target of this article, have specific traits which shape-up their control requirements. The entire field is covered by sprinklers located on top of riser pipes, and spaced in triangular or rectangular arrangements. Risers are connected to a network of buried pipelines. In semiarid environments, the water source is typically located far away from the solid-set, and a collective pressurized network is used for water conveyance. A supply hydrant delivers water to the on-farm network of sprinklers. In some occasions, particularly in temperate climates, the water abstraction point is located just upstream of the solid-set. Solid-sets are typically divided in a number of irrigation blocks which are irrigated in a sequential fashion. This permits to decrease the discharge required to irrigate the field, exploit a large fraction of the time available for irrigation and, hence, reduce the system cost. Irrigation controllers automatically operate the block valves according to a schedule previously programmed by the farmer. When using manually operated controllers, farmers input the irrigation start time, the frequency and the irrigation time or volume to be applied to each block.

A specific trait of solid-sets is that irrigation performance heavily depends on meteorological conditions. Wind speed has been shown to reduce irrigation uniformity. In combination with variables such as air temperature, relative humidity and solar radiation, wind speed also determines wind drift and evaporation losses (WDEL). Other pressurized irrigation systems show variable degrees of meteorological dependence. Drip irrigation applies water directly to the soil surface (or to the interior of the soil), and is therefore unaffected by the usual range of meteorological conditions. Centre pivots and moving laterals are much less affected by meteorology than solid-sets. Regarding WDEL, in the average conditions of Zaragoza, Spain, the experimental work reported by Playán et al. (2005) permits to estimate that average day time and night time solid-set losses amount to 15 and 5%, respectively. For irrigation machines, losses amount to 9 and 3% for day and night conditions, respectively. Differences in drop size distribution and drop trajectories are responsible for these differences in WDEL. Regarding the wind effect on uniformity, solid-sets are also in worse conditions, since sprinkler overlapping is much more intense in irrigation machines. As a consequence, avoiding periods of unfavorable meteorological conditions is a clear target for solid-set irrigation controllers.

The most advanced commercial controllers applied to solid-sets show some progress towards this objective. A local wind sensor can detain the execution of an irrigation schedule if the wind speed surpasses a given threshold. This is an interesting but somehow risky procedure: in some cases irrigation needs to proceed despite the unfavorable meteorology in order to protect crop yield. Irrigating under low uniformity and high WDEL requires consideration of the resulting low application efficiency. More water needs to be applied under these conditions. The integration of all these issues remains a challenge, particularly in windy areas. In the difficult meteorology of the central Ebro basin, Faci and Bercero (1991) recommended to stop solid-set irrigation for winds exceeding 2 m s^{-1}. It is not rare to find meteorological stations in the area with long-term yearly wind speed averages exceeding this threshold.

In an attempt to respond to these challenges, Zapata et al. (2009) and Zapata et al. (2013a) have developed advanced solid-set irrigation controllers based on simulation models. These controllers have been tested in simulated and experimental conditions. As a follow-up and a generalization of those developments, this paper contains:

- An overview of the current opportunities for the adoption of such controllers, mostly derived from technological developments;
- A description of possible designs for application in farms and in water users associations (WUAs);

- A discussion on strategic alternatives for these designs; and
- An analysis of the current bottlenecks requiring action in the fields of research, development and innovation.

OPPORTUNITIES

Solid-set irrigation systems

equipped with on-farm automation devices

The abovementioned data on progress of pressurized irrigation in general and solid-sets in particular sets the scene for a relevant case for technology and business development related to irrigation management. Dechmi et al. (2003) published the results of interviews performed in 1998 at La Loma de Quinto WUA, Ebro valley, Spain. This WUA is equipped with solid-sets, center-pivots and linear moves. According to that study, 86% of the farmers did not use any irrigation automation system. In these days, virtually all old and new solid-sets in the Ebro valley have been equipped with automation devices commanded by an irrigation controller. The use of automation devices responds to the progressively high ratio of labor *vs.* automation costs and to the decline in net benefit obtained from field crops (at least till the first decade of this century). These factors, combined with recent progress in irrigation modernization, have led farmers to crop a number of solid-set plots, each of them equipped with a manual irrigation controller which needs to be updated every week. The limited familiarly of many farmers with the controller interface accentuates the abovementioned dispersion in observed ARIS (Salvador et al., 2011). Despite constant progress in irrigation technology and large investments in automation, irrigation scheduling is not yet properly implemented. This constitutes at the same time a challenge and an opportunity. The opportunity lies on the generalization of solid-sets equipped with on-farm automation devices: automatic valves and controllers. The challenge lies on the capacities of these controllers, their poor human interface, and farmers' technological limitations.

Agrometeorological networks

In the last third of the twentieth century it became clear that real-time agrometeorological data would be required to guide irrigation decision making. The first large-scale network of automated agrometeorological stations was developed in California in 1985 by CIMIS (California Irrigation Management Information System). Its goals included disseminating irrigation requirements and promoting irrigation scheduling. A number of countries followed this example. Agrometeorological stations in such networks often record semi-hourly or hourly averages of at least air temperature and relative humidity, wind speed and direction, incoming solar radiation and cumulative precipitation. Irrigation advisory services have been built around these meteorological networks to advise farmers on the right amount of water to apply to their crops. Along the years, different media have been used to disseminate this information: from newspapers and radio to internet. Today, information is widely accessible from databases and can be used in almost real-time applications. Such systems are available in many areas of the world, creating a clear opportunity for irrigation scheduling and control applications.

Communications, including remote control

The rural sector is characterized by a low density of information scattered throughout a large territory. Pressurized collective networks often install telemetry / remote control (TM/RC) systems operating on mobile phone networks or on dedicated radio connections. The capacities of these systems are quite varied. In some cases, their use is restricted to the conveyance network; very often, hydrants can be remotely operated and their water meter readings automatically registered. The last step in remote control is the integration of the valves controlling irrigation blocks in on-farm systems. This last step is infrequently adopted, but it permits to fully schedule and operate solid-set irrigation from a WUA computer. A TM/RC system including distributed sensing of environmental variables (such as wind speed) can permit site-specific irrigation adapted to small-scale variations in evapotranspiration and solid-set irrigation performance. Additionally, the TM/RC system can be very useful in the optimization of energy consumption at the network's pumping stations.

Specialized WUA management databases

Playán et al. (2007) analyzed the evolution of WUA practices regarding information technologies, and reported on a software application for the daily WUA management While the use of databases was scarce by the end of the twentieth century, virtually all WUAs in the Ebro valley are today using such tools for water allocation and planning, accessing geographical information systems and filing water orders to their supply canals. WUA management databases contain registers of water users, land tenure, collective network layout, on-farm irrigation structures and crops. These databases permit to automatically produce updated information leading to the establishment of irrigation schedules. This creates an opportunity for the WUA to offer a service for centralized irrigation management. The quality of this service will depend on the quality of the data stored in the database, for which both the farmers and the WUA are responsible. Farmers' crop declaration at the beginning of the irrigation season has enjoyed growing acceptance in the past years, owing to the need for WUA water allocation planning.

Computer models for crops and irrigation systems

A new generation of advanced irrigation controllers can build on the success of two parallel research lines on simulation models: sprinkler irrigation and crops. Sprinkler irrigation simulation is often based on the application of ballistics to the drops emitted by a sprinkler (Fukui et al., 1980; Seginer et al., 1991). Drops are assumed to travel independently from the nozzle to the soil surface or the crop canopy, subjected to an initial velocity vector, a wind vector, the action of gravity, and the resistance force. The equations of motion are commonly solved using a Runge–Kutta method. Carrión et al. (2001) and Montero et al. (2001) released the SIRIAS model and provided specific details and simulation arrangements to best represent the action of wind. Playán et al. (2005) presented a series of empirical predictive equations for wind drift and evaporation losses which complemented the ballistic model. The output of this model is the spatial distribution of water application within a sprinkler spacing, along with the related performance indicators.

Crop modeling has emerged a useful tool to combine the processes leading to soil water balance, crop growth and crop yield, using mathematical equations implemented in software applications. In sprinkler irrigated areas, both simple and sophisticated crop models have been tested to evaluate their predictive capacity when coupled to soli-set sprinkler irrigation models. CropWat (Smith, 1992) is a simple approach to soil-water-yield modeling. This model considers a single soil water layer and ignores nutrient stresses. Dechmi et al. (2010) showed that the complex crop growth simulation models EPIC (Williams et al., 1984) and DSSAT (Jones et al., 2003) can improve the results of the simple model Ador-Crop (Dechmi et al., 2004a), based on CropWat. However, Ador-Crop proved very useful in improving irrigation performance when governing an advanced controller (Zapata et al., 2013a). Complex crop models simulate all processes involved in crop growth considering very detailed soil, crop, weather and management that require very accurate and numerous inputs. As a consequence, their performance heavily depends on the availability of detailed site-specific information. Crop models use irrigation water as one of their inputs, and produce the time evolution of crop water requirements and an estimate of crop yield.

The combination of both models has a multiplying effect. A regular network of simulation points is established within a sprinkler spacing (typically a 5 x 5 matrix), and a crop simulation model is instanced at each point. Each crop simulation uses the simulated irrigation depth at the point to establish its own hydrological balance and to determine its own crop water requirements. This is how both models are coupled for crop irrigation management purposes. Water stress appears at different times in different areas of the sprinkler spacing, and irrigation is applied when a certain fraction of these points is water stressed (Dechmi et al., 2004a and 2004b). The coupled model can be used to optimize irrigation performance indexes, crop yield or a combination of both (water productivity). Dechmi et al. (2004a and 2004b) calibrated and validated the coupled model. Zapata et al. (2009) applied it to collective irrigation systems using a structured, hierarchical description of land use and irrigation infrastructure. These authors used different strategies to simulate the centralized irrigation scheduling of part of a WUA. Their results showed that the proposed technology can lead to significant water conservation respect to individual farmer scheduling.

Time slack on network and on-farm design

On-farm sprinkler irrigation systems and collective networks are commonly designed to apply water at a faster rate than irrigation requirements. This results in a certain time slack in irrigation scheduling. Depending on the fraction of time slack, the irrigation timing can be negotiated with the WUA or selected on pure demand (Clemmens, 1987). Time slack at the on-farm system and at the water inlet is required to optimize irrigation performance. Sprinkler irrigation farmers can select the irrigation periods leading to optimum efficiently while timely satisfying crop water requirements. Irrigation networks with sufficient time-slack lead to high performance, but require large investments (Zapata et al., 2007; Merriam et al., 2007; Daccache et al., 2010). Farmani et al. (2007) reported that designing for rotational operation can reduce investments up to 50% as compared to on-demand designs.

Zapata et al. (2009) reported that farmers may take advantage of the time slack to apply more water than required. The need for frequent update of manual irrigation controllers, and uncertainty over most of the overwhelming number of variables required for irrigation scheduling can explain this practice (English et al., 2002; Zapata et al, 2013a). Advanced irrigation controllers can take advantage of time slack by automatically producing and applying real-time schedules, minimizing human subjectivity.

Exploiting some of these opportunities: a case study

The Almudévar WUA was surface irrigated till 2008, with 94% of the total area irrigated by blocked-end borders. This 3,744 ha WUA is operated by many part-time farmers and a few professional farmers (operating on leased land). This area was recently modernized and entirely transformed to pressurized irrigation (94% of solid-sets). Electric power is used to pressurize all irrigation water. The modernization process was completed by the end of 2010. The first phase of the modernization project was land consolidation. Land tenure passed from 610 owners of 2,339 plots to 502 owners of 905 plots, resulting in 71% of the farmers owning plots larger than 5 ha. This new land ownership structure was required to afford irrigation modernization costs, largely dependent on plot size. The Almudévar WUA has a TM/RC allowing remote scheduling of all hydraulic valves (collective and on-farm) from the WUA office. An arranged-demand scheme is applied to manually elaborate daily/weekly schedules for WUA plots which are automatically executed using the TM/RC system. The virtual elimination of irrigation labor requirements is locally perceived as one of the most important outcomes of the modernization process.

Almudévar WUA personnel organize farmers' irrigation demands taking into account their preferences, the evolution of energy costs and the available power. The average Seasonal Irrigation Performance Index (SIPI, an estimate of irrigation efficiency) for major crops has increased from 70% in surface irrigation (Faci et al., 2000) to 87% right after the modernization process (Stambouli, 2012). Irrigation execution automation has permitted to quickly evolve from an inefficient, obsolete WUA to an innovative WUA exploiting new technologies. The next step, automating irrigation scheduling, could render this WUA more efficient in water and energy, more productive and more responsive to environmental changes. It would also eliminate the burden of manually scheduling each of its 2,200 valves.

CONTROLLER DESIGNS
DRIVEN BY SIMULATION MODELS

Current solid-set irrigation controller designs are based on manual elaboration of irrigation schedules. Basic controller set-up data include the number of irrigation blocks and the respective automatic valves. Farmers create a schedule by deciding the irrigation time for each block, the frequency (typically the days of the week when the schedule will be executed) and the starting time of the irrigation sequence. These controllers produce rigid irrigation schedules, which are implemented regardless of meteorology. In specific cases, these controllers can include sensors allowing volume-based irrigation. As previously discussed, controllers are available in the market which permit to suspend/resume programme execution responding to specific sensors (i.e., wind speed). In the following sections, two model–driven designs are presented for on-farm and WUA applications, respectively.

An on-farm controller design

The design presented in Figure 1 corresponds to an autonomous solution for a solid-set supplied by an electric pumping station. This design only requires external evapotranspiration input. The controller uses information from the electricity contract to minimize energy costs. The farmer can gain manual control of the system to force an irrigation event, prevent irrigation during a certain time or perform a manual fertigation. The controller uses information on the plot structure, division in blocks and irrigation equipment. Irrigation events are scheduled using local, real-time meteorological information. In the context of an on-farm controller, the computing capacities may be limited. As a consequence, the system can be guided by the tabulated results of an irrigation simulation model. Local wind statistics can be used to establish simple irrigation management rules based on the frequency and duration of windy spells. Crop models can also be replaced by simple water balance simulation models. Rules based on thresholds for Potential Application Efficiency of the low quarter (PAElq) can be used to guide irrigation decision making. A strategy very similar to this design was field implemented as strategy T1 in Zapata et al. (2013a). T1 performed better than manual irrigation based on the weekly recommendations of an irrigation advisory service. The controller computing capacity could be expanded by the use of a remote computer in continuous communication with the on-farm controller. This would permit real-time use of simulation models and would at the same time limit the risk of vandalism against expensive field equipment.

A WUA controller design

Figure 2 presents a more complex configuration, responding to the goal of governing a WUA through its TM/RC system. The system requires the use of one or several computers devoted to irrigation and crop simulations. The WUA structure, in terms of collective and on-farm irrigation equipment, can be obtained from an on-line connection to the WUA management database. The irrigation controller can in turn feed the management database with the time evolution of water application to the different plots. This controller design can make extensive use of local sensors, taking advantage of the spatial variability of different meteors, and their influence on crop water requirements and solid-set irrigation performance. Measured pressure levels in the network can also be related to solid set performance, and can be used to make decisions on water allocation to additional plots. Hydraulic network simulation models can be applied to guide this process, in combination with measured values. Irrigation and crop models with different degrees of complexity can be used to support real-time irrigation decision making. Under this controller design, plot irrigation will proceed exploiting moments of low energy costs, suitable meteorological conditions and adequate network pressure. Controlling the irrigation of a whole WUA (or a large part of it) permits to make full use of the abovementioned opportunities. This design can be readily compared to strategy T2 in Zapata et al. (2013a), which outperformed the rest of studied alternatives.

EXPLORING DESIGN ALTERNATIVES

Independent *vs.* slave on-farm controllers

The on-farm controller design above can be formulated as a stand-alone device or as part of a distributed irrigation control operation. A central scheduling service can produce and update farm-specific schedules and distribute then to a series of slave controllers governing solid-set plots distributed over a large irrigated area. Under this configuration, the slave on-farm controller can sense the local environment, transfer this information to the server, and receive irrigation schedules together with the updates required to respond to an ever changing environment. The server can blend internet and local information, and make intense computational use of simulation models. The combination of servers and slave controllers paves the way for the establishment of companies providing irrigation execution services supported by automatic controllers. Specific computer and portable device applications can provide farmers with user friendly interfaces. Under this configuration, the slave controller needs no human interface, thus reducing cost and the risk of vandalism.

Measuring *vs.* simulating water deficit

Determining soil water deficit leads to the elaboration of irrigation schedules protecting farmers' income and natural resources. Current developments in sensors and wireless communications permit to conceive solid-set irrigation controllers based on intensive soil water measurements. Such systems obtain real-time water deficit measurements at a number of observation points. In solid-set irrigation, a strong variability in water application can be observed within each sprinkler spacing, within an irrigation block (owing to differences in sprinkler pressure) and among irrigation blocks (due to differences in inlet pressure, irrigation time and meteorological conditions during irrigation). As a consequence, the number of soil water measurement points required to guide irrigation control in solid-sets remains unknown. The local calibration and maintenance of soil water probes, and the establishment of local soil water irrigation thresholds require a site-specific effort which needs to be confronted with the typically low economic return of solid-set irrigated crops. The use of simulation models to estimate soil water deficit and its relation to crop yield requires intense field measurements at the calibration and validation phases (Playán et al., 2006; Zapata et al., 2013a). However, these models have proven useful to govern solid-set irrigation controllers using sub-regional meteorological variables and simple crop information (Zapata et al., 2013a). Sensors and simulation models could eventually be combined for optimum results.

Controlling solid-sets only *vs.* combinations of pressurized irrigation systems

Irrigation controllers designed to control farms or WUAs equipped with a combination of solid-sets and other pressurized on-farm systems can attain high levels of overall irrigation performance. This is due to the fact that solid-sets are more sensitive to environmental conditions than sprinkler irrigation machines and drip irrigation systems. An advanced controller can respond to periods of intense wind and/or evaporative demand by switching irrigation to plots equipped with drip irrigation systems. Centre-pivots and moving laterals could be irrigated under intermediate conditions, and solid-sets could be irrigated when they show optimum performance (night time, calm periods). If an advanced controller governs different farms, these policies will need the approval of all concerned farmers. Sprinkler irrigation under high WDEL and low uniformity conditions requires additional water application to attain the same yield. It is therefore in the interest of all farmers to maximize the average water productivity of all plots and irrigation systems. Maximizing water productivity requires the implementation of water allocation algorithms based on the analysis of collective water requirements. Under harsh environmental conditions, individual irrigation action may result in low collective efficiency and water productivity.

Irrigation automation *vs.* optimization of water productivity and sustainability

The proof of concept reported by Zapata et al. (2013a) served the purpose of verifying that a computer can effectively use crop and irrigation models to take full control of solid-set irrigation. As a consequence, the objective of attaining full irrigation automation now seems accessible. In order to maximize the benefits of this technology, it is very important to go beyond this point, and seek the optimization of water productivity and sustainability. The reduction of irrigation water application and energy use and cost adds to both aspects. Water and energy use are directly related in a given irrigation project. The worldwide record increment of modern irrigation during the 20th century took place in a context of low energy cost. At the outset of the 21st century, regulations induced by the rapid growth in energy demand and by constrained supplies of fossil fuels have resulted in increasing energy prices (Rajagopal and Zilberman, 2007).

As an example, the share of irrigation energy use in Spain has increased from 22% to 32% of the total agricultural energy demand between 2001 and 2012. Most of this 46% increase can be attributed to the ambitious irrigation modernization policies enforced during than period (IDAE, 2008). The energy dependence of pressurized irrigation systems has been aggravated by the dramatic rise in electricity prices. The derogation of special irrigation electricity rates, the preferential binomial tariffs, and the liberalization of the electricity market in 2008 (IDAE, 2008) severely increased energy costs in modernized WUAs (Abadía et al., 2008). The complexity of the electric tariff for the Almudévar WUA is presented in Figure 3, as example of energy tariffs in Spain for WUAs. Electric tariffs are arranged in six levels characterized by very different energy and power costs. The cost of the cheapest tariff represents 38% of the cost of the most expensive tariff. This scenario changes if energy sources other than electricity are used. The cost of diesel does not show periodic short-time patterns. Wind and solar renewable energies attain maximum production during the daytime, when sprinkler irrigation is most exposed to environmental conditions. A water and energy limited future will trigger the application of advanced control technologies to irrigated agriculture (Evans and King, 2012). Advanced irrigation controllers can integrate all factors leading to water and energy productivity and sustainability, such as crop water requirements and yield response, time-variable energy tariffs, environmental constrains, and hydraulic and energy performance.

Targeting unskilled *vs.* advanced farmers

Irrigation scheduling rests on technical concepts such as evapotranspiration, crop water requirements or application efficiency. While these concepts constitute the basic jargon of irrigation technicians, their use by farmers very much varies from area to area. In many areas of the world, farming and irrigation are often performed by part-time farmers. For instance, in 2010 in Spain there were 2.23 million farmers (Eurostat, 2012). Considering their partial dedication to agriculture, this figure is equivalent to 0.89 million full-time farmers (40% of the total). This illustrates the fact that full-time farmers are a small fraction of the total number of farmers. The productive strategies of full- and part-time farmers are intrinsically different. Full-time farmers seek maximum benefits through input efficiency (fertilizers, irrigation water, labor…), while part-time farmers are very interested on reducing the time they devote to agriculture.

On the other hand, farmers can be classified by their technical capacities. In general, full time-farmers will be better trained than part-time farmers. The same applies to different areas of the world. Developed countries will likely count on advanced farmers, while many farmers in developing countries can have limited conceptual irrigation skills. Even in developed countries, irrigation scheduling skills are not abundant. As an example, in the Ebro valley of Spain, the full cost of irrigation modernization is 10 - 15 k€ ha^{-1} (collective network plus on-farm solid-set). In the case of technology adverse farmers, the irrigation contractors will often finalize system installation by introducing a sequential, non-stop, perpetual schedule in the controller. When these farmers want to irrigate, they just open the general valve. The controller will sequentially irrigate the system blocks till the farmer closes the valve again. In these cases, irrigation scheduling consists on manually opening and closing the system valve for the time the farmer judges adequate.

Different controller designs can provide solutions to the expectations of different types of farmers. Very simple irrigation controllers, requiring limited input and user's interaction can respond to the scheduling needs of part-time and unskilled farmers. Full-time and advanced farmers may need a controller with sufficient flexibility to make proper use of the farmer's experience and knowledge. This knowledge can be related to crop cycle or to the current crop water status. The needs of different kinds of farmers define different controller designs, characterized by the expected farmer interaction. These types of controllers could coexist in a given irrigation project, responding to the variability in farmers' approach and capacities.

IDENTIFYING BOTTLENECKS

Research needs

Previous works on linking crop and irrigation models indicated that complex crop models resulted in a better prediction of the variability in crop yield (Dechmi et al., 2010). Research will be required to establish the conditions in which simple or advanced crop models are required at different scales. Complex models will permit to explore additional sustainability aspects, such as the interaction between irrigation and pollution. Models' capacity to simulate nutrient cycles under intensive irrigation systems will have to be specifically evaluated. Despite all these exciting possibilities, the use of such models is currently limited by the integration of the computer code. Even if the code is public, coupling the required model often requires intense code manipulation. Object-Oriented Programming or Dynamic Link Libraries are needed to set-up a crop, to advance simulation by one day (updating meteorological, hydrological and agronomic variables), and to finalize crop simulation. These difficulties triggered the development of Ador-Crop as an Object-Oriented evolution of CropWat, and were recently signaled by Bergez et al. (2012), when discussing the integration of the STICS crop model in coupled bio-decisional models.

Calibration requirements need to be properly addressed to facilitate controller adoption by users. Ballistic irrigation model results have been shown to depend on the sprinkler manufacturer (Playán et al., 2006). A few sprinkler models have so far been calibrated. In addition, new sprinklers reach the market virtually every year, specializing on issues such as low operating pressure. The situation is even more complicated for crop models. While simple models – such as CropWat – can be readily used in a variety of conditions, complex models do not only require more intense input data collection, but also local calibration (Dechmi et al., 2010).

Research efforts have been discussed in this article for different types of pressurized systems. Advanced control of large irrigated areas will require a software integration of all efforts. Such combinations will lead to new benchmarks in productivity and sustainability, but the required software integration effort will be relevant. Simulation models and wireless sensors will populate these future developments adapting to a variety of irrigation systems, crops and productive orientations.

Local-scale meteorological variability has received scientific growing attention during the last years. For instance, wind spatial variability is much higher than that of other meteors of agricultural interest, such as air temperature and relative humidity (Martínez-Cob et al. 2010). Wind speed influences both crop water requirements and sprinkler irrigation performance. Sánchez et al. (2011) analyzed the effect of local-scale wind spatial variability at WUA scale, with the objective of improving sprinkler irrigation design and management. Regarding wind effects on evapotranspiration, Zapata et al (2013b) analyzed a 225 ha commercial orchard and reported wind spatial differences amounting to 55%. This resulted in intra-farm reference evapotranspiration variability of 17%. Revealing this variability is the first step to develop and test management strategies leading to optimum WUA performance. Such strategies may for instance imply concentrating irrigation in wind-sheltered areas during windy spells.

Technology needs

Controller manufacturing companies have traditionally focused on their own hardware designs. However, in these days there are a number of alternatives for the controller hardware to be installed at the farm. Open-hardware platforms based on open-software stand as powerful alternatives. Prototyping platforms can be used to design upgradable, resourceful, low-cost and internet-ready field controllers. *Arduino* is an example of such platforms (www.arduino.cc), which is enjoying wide success among the scientific and technological community for a wide variety of control applications. Open approaches exponentially increase opportunities for peer to peer cooperation. An internet search on *Arduino* irrigation applications currently returns thousands of hits. These applications focus on residential garden irrigation, and mainly address remote control and surveillance issues. Professional irrigation seems to have quite a bit to learn from this open source community, at least in what refers to human interfacing.

The wide commercial offer on TM/RC systems currently exploits proprietary developments with very limited intercommunication capacities. Many cases are known in Spain in which WUAs having installed different TM/RC systems their pressurized networks end up with completely isolated systems, unable to communicate. The International Standardization Office, through subcommittee ISO/TC23/SC18 "Irrigation Techniques", has created a working group on "Remote monitoring and control technologies". This group aims at releasing a standard on TM/RC systems for irrigation. The completion and application of such a standard is a major requirement for the use of TM/RC systems in WUA controllers.

Innovation needs

The new generation of irrigation controllers will require supporting companies to provide a new set of services. Some of these services, like irrigation advising, are already offered in some areas of the world, particularly for cash crops. A business model can be based on running irrigation scheduling services connected to a number of disseminated on-farm slave controllers. Such a company needs to ensure proper functioning of the scheduling system, and needs to keep on-farm controllers functional. Additional services can be based on adjusting the irrigation schedule to observed field conditions, but can add fertigation or general agronomic advice. For WUA controllers, farmers can voluntarily subscribe to the WUA advanced scheduling services. The WUA or a hired services company could offer subscribed farmers a flat rate per volume of water, regardless of the time variations of the electric tariff.

The concept of solid-sets driven by simulation models is receiving interest on the part of the end-users. However, this is a radical change respect to the current conditions. Once the proof of concept phase has been surpassed, actions need to be taken to demonstrate this approach in real-scale conditions. Public and private interests need to be reconciled to set the proposed model in action.

Farmers and WUAs

The current socioeconomic farming context favors the implementation of advanced irrigation controllers: adequate prices for agricultural commodities, high labor and water costs, increasing energy prices and a growing environmental liability. In this context, professional, progressive farmers are required, which are determined to take advantage of research and innovation products. At the WUAs, in addition to bold leadership, irrigation specialists are required which can establish the link to new technologies. The policy relevance of preserving water resources from depletion and pollution requires regulations favoring the deployment of irrigation controllers for pressurized irrigation in general and for solid-sets in particular. Advanced irrigation controllers can provide an easy access to the environmental certification of farms and producers in what respects to irrigation water.

CONCLUSIONS

Irrigation controllers for pressurized systems are quickly changing to respond to water, energy and agronomy challenges and to implement new technologies. Urban landscaping and greenhouses are leading this process, with a number of scientific and commercial developments mainly driven by evapotranspiration and/or soil water measurements. Developments in orchards, irrigation machines and solid-sets still remain in the science and technology domain. Opportunities are currently piling-up for the development of solid-set controllers driven by simulation models. A number of technologies have materialized which permit fast-track progress in automating solid-set irrigation control and at the same time progressing in irrigation productivity and sustainability. Designs have been presented for on-farm and WUA controllers, exploiting not only simulation models, but also developments in communications and electronics. A series of design alternatives have been discussed, offering an array of possible configurations responding to the site-specificities characterizing irrigated agriculture. Advanced controllers are not just fit for advanced societies. They can effectively respond to the needs of unskilled farmers in low-technology societies. Advanced controllers can bridge the irrigation learning curve, and produce relevant improvements respect to manual programming, particularly if farmers lack basic irrigation skills. A number of bottlenecks have been identified in the research, technology and innovation domains. Software/hardware developments, calibration, standardization and demonstration requirements, development of new business models and farmers' expectations, and policy action have been listed as critical points for the deployment of this technology. Despite the reported success of the proof of concept of these advanced controllers, additional experimentation is required before large scale applications can be planned.

ACKNOWLEDGEMENT

This research was funded by the Government of Spain through research grant AGL2010-21681-C03-01. The research contract of S. Lecina was funded by the National Institute for Agricultural and Food Research and Technology (INIA), Spanish Ministry of Economy and Competitiveness.

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LIST OF FIGURES

Figure 1. Schematic representation of an on-farm solid-set irrigation controller design driven by simulation models.

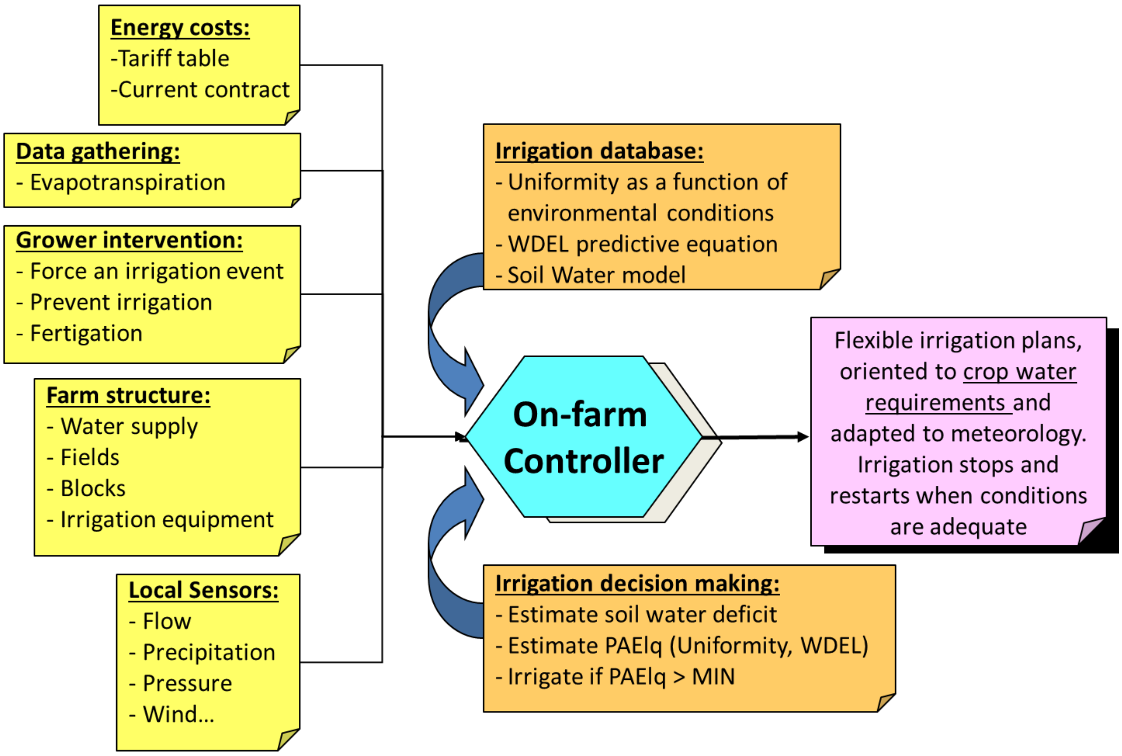


Figure 2. Schematic representation of a WUA solid-set irrigation controller design driven by simulation models.

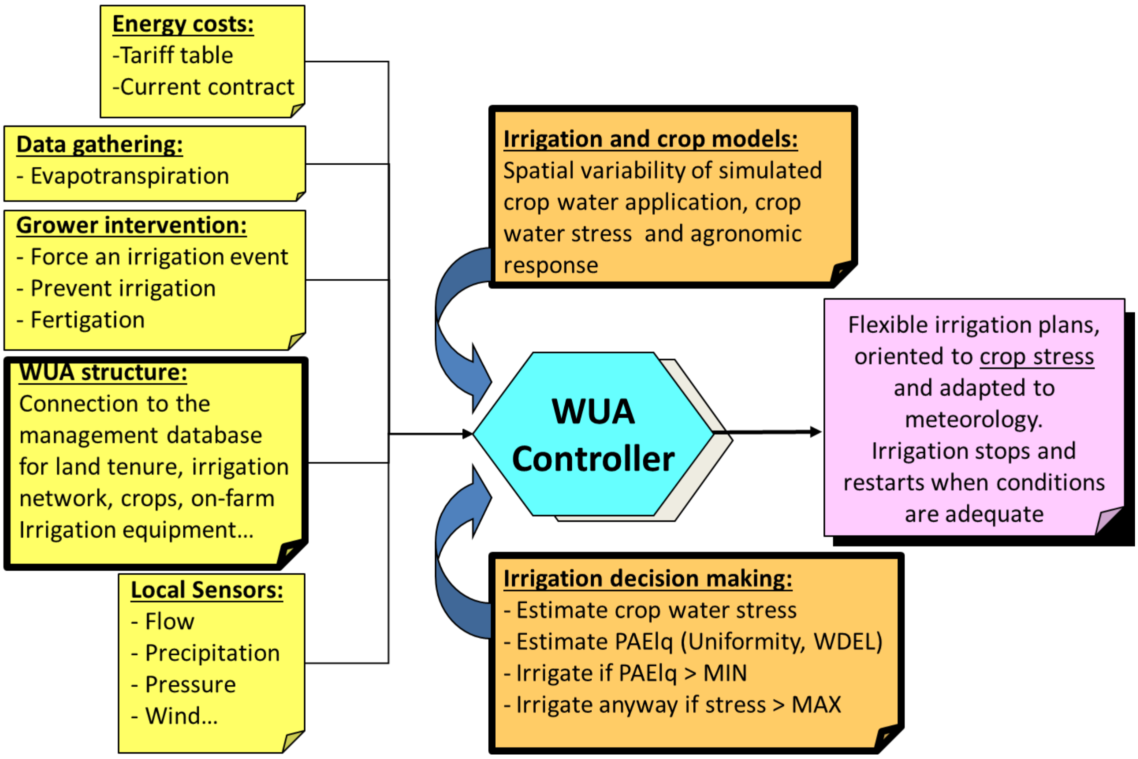
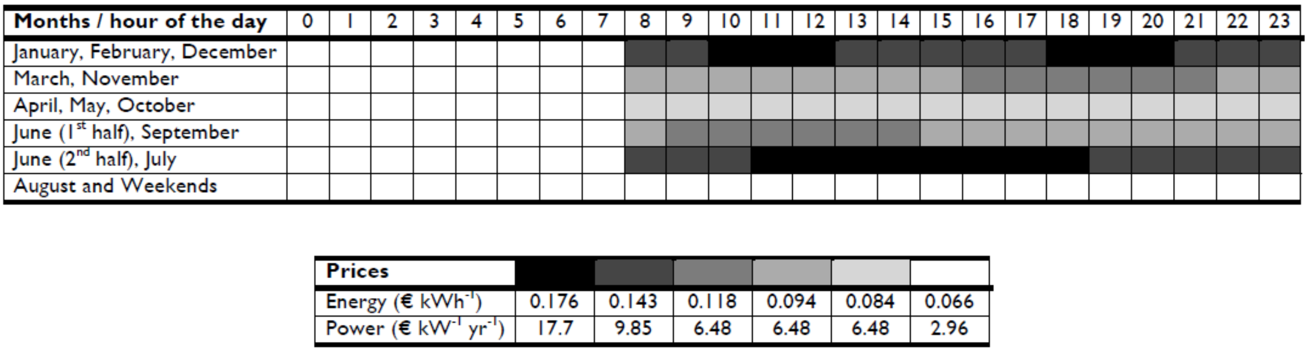


Figure 3. Time distribution of electricity cost along the year and along the day in the Almudévar Water Users Association.



Months / hour of the day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
January, February, December									▓	▓	█	█	█	▓	▓	▓	▓	▓	█	█	█	▓	▓	▓
March, November									░	░	░	░	░	░	░	░	▒	▒	▒	▒	▒	▒	░	░
April, May, October									·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
June (1st half), September									░	▒	▒	▒	▒	▒	▒	░	░	░	░	░	░	░	░	░
June (2nd half), July									▓	▓	▓	█	█	█	█	█	█	█	█	▓	▓	▓	▓	▓
August and Weekends																								

Prices	█	▓	▒	░	·	
Energy (€ kWh^{-1})	0.176	0.143	0.118	0.094	0.084	0.066
Power (€ kW^{-1} yr^{-1})	17.7	9.85	6.48	6.48	6.48	2.96