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Tesis Doctoral

Gestión del agua en sistemas de riego por aspersión en el valle de Ebro: análisis de la situación actual y simulación de escenarios

Water management in sprinkler irrigation systems in the Ebro valley: current situation and scenario simulations

Memoria presentada por: **Farida Dechmi**

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A

mes parents

frères et sœurs

neveux et nièces

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ABSTRACT

In all irrigation systems, adequate irrigation design and management are required to promote an efficient use of available water, increase crop production and minimise deep percolation losses. In this research, a contribution to water conservation in sprinkler irrigation systems was performed. An analysis of water use and irrigation performance in the Loma de Quinto District (LQD) is presented. This district is located in the Ebro valley (NE Spain), and irrigates 2,606 ha with a wide variety of sprinkler irrigation systems. This analysis represents a contribution to the Diagnostic Analysis phase of an incipient Management Improvement Program for the LQD. In Chapter I, the irrigation management problems at the LQD and the factors affecting local water management were analysed. The high cost of irrigation water in relation to crop revenues, the technical deficiencies of the irrigation systems, and the limitations imposed by the climate and soils appear to be major causes of the water management problems identified in the LQD.

In chapter II, the analysis of irrigation water use focused on two additional issues: irrigation uniformity and the relationship between water use and crop yield. The results of the irrigation evaluations indicated that the solid-set Christiansen Coefficient of Uniformity (*CU*) was severely reduced by wind speed. However, in centre-pivots and linear-moves *CU* was slightly higher in evaluations with wind speeds between 2 and 6 m s^{-1} than under calm conditions. The evaluation data set was used to validate a ballistic solid-set sprinkler irrigation simulation model. The model was used to extend the evaluation results to all the solid-set plots in the LQD. Simulations of irrigation scheduling performed on a limited number of plots detected a 12 % decrease in crop yield due to deficit irrigation and/or large irrigation intervals. The introduction of an optimal irrigation schedule (avoiding yield reductions) would imply increasing the alfalfa seasonal irrigation depth by 101 mm, and applying light, frequent irrigation events.

A field experiment was performed to study the effect of the space and time variability of water application on solid set sprinkler irrigated corn yield (Chapter III). A solid-set sprinkler irrigation setup typical of the new irrigation developments in the Ebro basin of Spain was considered. The results of this research showed that large percentages of the *CU* variability and the wind drift and evaporation losses were explained by the wind speed alone. No evidence was found proving that the soil diminishes the heterogeneity induced by the irrigation water distribution. Results indicated that grain yield variability was largely dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season. The irrigation depth resulting from irrigation events applied beyond the flowering stage was significantly correlated with grain yield.

The development of a coupled crop model (Ador-Crop) and solid set sprinkler irrigation model (Ador-Sprinkler) is presented in Chapter IV. Ador-Crop incorporates many of the features developed in the well-known CropWat model. Relevant improvements include the use of thermal time and the input of daily potential evapotranspiration. Ador-Sprinkler applies ballistic theory to determine water distribution resulting from sprinklers subjected to a wind vector. The model was calibrated with field experiments performed in two adjacent plots on a corn crop irrigated with sprinklers equipped with 4.4 and 2.4 mm nozzles in a triangular spacing of 18 x 15 m. Once the calibration phase was completed, Ador-Sprinkler adequately predicted irrigation water distribution during the whole corn development cycle. The crop model was validated through a comparison with CropWat. Both models produced similar yield reduction results. Regarding the coupled model validation, the plot of soil available water *vs.* measured and simulated yield reduction resulted in similar features. The coupled model explained 25 %** of the variability in measured yield reduction.

The model was exploratorily applied to a number of design and management issues in solid-set irrigation (Chapter V). The most relevant results are related to the characterization of advanced irrigation scheduling strategies. The differences in crop yield and water use derived from conducting irrigations at different times of the day were estimated for two locations strongly differing in wind speed. Irrigation guidelines were established in these locations to relate gross water use and water stress induced yield reductions. Simulations were also applied to estimate the value of wind speed thresholds for irrigation operation. In the windy location, a threshold of 2.5 m s^{-1} resulted adequate to control yield reductions and to minimize water use.

RESUMEN GENERAL

En todos los sistemas de riego, un adecuado diseño y manejo permiten hacer un uso más eficiente del agua disponible, maximizar la producción y limitar las pérdidas de agua por percolación profunda. En este trabajo se pretende contribuir a la mejora del uso del agua en el riego por aspersión. En primer lugar, se presenta un análisis del uso del agua y la calidad del riego en la comunidad de regantes de la Loma de Quinto. Esta comunidad está localizada en el valle de Ebro (NE España), y usa una gran variedad de sistemas de riego por aspersión para regar 2.606 ha. El presente estudio es una contribución a la fase de análisis y diagnostico de un incipiente Programa de Mejora de la Gestión en la Loma de Quinto. En el Capítulo I, se analizaron los problemas del manejo de riego y los factores que afectan al uso el agua. El elevado coste del agua de riego en relación con el margen bruto de los cultivos, las deficiencias técnicas de los sistemas de riego, y las limitaciones impuestas por el clima y los suelos parecen ser las causas principales de los problemas de uso del agua identificados.

En el Capítulo II, el análisis de la comunidad se ha extendido para incluir evaluaciones de riego, simulaciones del riego en coberturas totales de aspersión, y el estudio de la relación entre la programación del riego y el rendimiento de los cultivos. En coberturas totales de aspersión, la uniformidad de riego se redujo fuertemente con la velocidad del viento. Sin embargo, en pivotes y máquinas de desplazamiento lateral el coeficiente de uniformidad de Christiansen (*CU*) resultó ser ligeramente más elevado en evaluaciones con vientos de entre 2 y 6 m s^{-1} que en condiciones de calma. Las evaluaciones de campo se utilizaron para validar un modelo balístico de riego por aspersión en coberturas totales. El modelo fue aplicado para extender los resultados de las evaluaciones de campo a todas las parcelas de Quinto con coberturas totales. La simulación de las prácticas de riego en un número limitado de parcelas detectó que el riego deficitario y/o los largos intervalos de riego resultaron en una reducción del rendimiento el 12 %. La introducción de una programación de riego óptima implicaría que la dosis de riego estacional de alfalfa aumentara en 101 mm, y llevaría a la aplicación de riegos ligeros y frecuentes.

Se realizó un experimento de campo para estudiar el efecto de la variabilidad espacial y temporal de la aplicación del agua sobre un cultivo de maíz regado con una cobertura total de aspersión (Capítulo III). Se utilizó una cobertura típica de los nuevos desarrollos de riego del valle del Ebro. Los resultados de esta investigación mostraron que porcentajes amplios de la variabilidad del CU y de las pérdidas de agua por evaporación y arrastre podían ser explicados por la velocidad del viento. No se encontraron evidencias que prueben que el suelo disminuye la heterogeneidad introducida por la distribución del agua de riego. Los resultados indicaron que la variabilidad del rendimiento del cultivo fue dictada en buena medida por el déficit de agua debido a la no-uniformidad de la distribución del agua durante el ciclo del cultivo. La lámina aplicada en los riegos realizados a partir de la floración del maíz estuvo significativamente correlacionada con el rendimiento del cultivo.

El desarrollo de un modelo de simulación que combina un modelo de cultivos (Adror-Crop) y un modelo de riego por aspersión en cobertura total (Ador-Sprinkler) se presentó en el Capítulo IV. Ador-Crop incorpora muchas de las características del modelo CropWat. Sin embargo, se han introducido mejoras sustanciales respecto del modelo original, como el uso de tiempo térmico para el crecimiento de los cultivos y la introducción de datos diarios de evapotranspiración de referencia. Ador-Sprinkler aplica la teoría balística para determinar la distribución de agua que resulta de aspersores sujetos a un vector de viento. El modelo se calibró con experimentos de campo en dos marcos de aspersión adyacentes de una cobertura equipada con aspersores provistos de boquillas de 4,4 y 2,4 mm de diámetro, dispuestos triangularmente con un espaciamiento de 18 x 15 m. Ador-Sprinkler predijo adecuadamente la distribución del agua de riego durante todo el ciclo del cultivo. El modelo de cultivos se validó a través de una comparación con CropWat. Ambos modelos predijeron una reducción del rendimiento similar. En cuanto a la validación del modelo combinado, la representación de los valores medidos y simulados de agua estacional disponible para el cultivo frente a la reducción de rendimiento resultaron similares. El modelo combinado pudo explicar el 25 %** de la variabilidad de la reducción de rendimiento medida.

Por último, el modelo fue exploratoriamente aplicado a un número de problemas de diseño y manejo del riego por aspersión (Capítulo V). Los resultados más relevantes fueron los que se obtuvieron de la caracterización de técnicas avanzadas de programación de riegos. Las diferencias en el rendimiento del cultivo y el uso del agua derivadas de regar a diferentes horas del día se estimaron en dos localidades con importantes diferencias en su exposición al viento. En estas localidades se desarrollaron curvas para relacionar el agua usada con el descenso del rendimiento de los cultivos. La simulación se aplicó también a la estimación de valores umbrales de viento para un manejo óptimo del riego. En la localidad más expuesta al viento el umbral de 2,5 m s^{-1} resultó adecuado para controlar la caída del rendimiento y para minimizar el uso del agua.

RESUM GENERAL

En tots els sistemes de reg, un adient disseny i maneig permeten fer un ús més eficient de l'aigua disponible, maximitzar la producció i limitar les pèrdues d'aigua per percolació profunda. En aquest treball es pretén contribuir a la millora de l'ús de l'aigua en el reg per aspersió. En primer lloc, es presenta una anàlisi de l'ús de l'aigua i la qualitat del reg en la comunitat de regants de la Loma de Quinto. Aquesta comunitat està localitzada a la vall de l'Ebre (NE Espanya), i fa servir una gran varietat de sistemes de reg per aspersió per regar 2.606 ha. El present estudi és una contribució a la fase d'anàlisi i diagnòstic d'un incipient Programa de Millora de la Gestió en la Loma de Quinto. Al Capítol I, es van analitzar els problemes del maneig de reg i els factors que afecten a l'ús de l'aigua. L'elevat cost de l'aigua de reg en relació amb el marge brut dels conreus, les deficiències tècniques dels sistemes de reg, i les limitacions imposades pel clima i els sòls semblen ser les causes principals dels problemes de l'ús de l'aigua identificats.

Al Capítol II, l'anàlisi de la comunitat s'ha estès per a incloure avaluacions de reg, simulacions del reg en cobertures totals d'aspersió, i l'estudi de la relació entre la programació del reg i el rendiment dels conreus. En cobertures totals d'aspersió, la uniformitat de reg es va reduir fortament amb la velocitat del vent. Però, en pivots i màquines de desplaçament lateral el coeficient d'uniformitat de Christiansen (*CU*) va resultar lleugerament més elevat en avaluacions amb vents d'entre 2 i 6 m s^{-1} que en condicions de calma. Les avaluacions de camp es van fer servir per a validar un model balístic de reg per aspersió en cobertures totals. El model va ésser aplicat per a estendre els resultats de les avaluacions de camp a totes les parcel·les de Quinto amb cobertures totals. La simulació de les pràctiques de reg en un nombre limitat de parcel·les detectà que el reg deficitari i/o els llargs intervals de reg van resultar en una reducció del rendiment el 12 %. La introducció d'una programació de reg òptima implicaria que la dosis de reg estacional d'alfals augmentaria en 101 mm, i portaria a l'aplicació de regs lleugers i freqüents.

Es va realitzar un experiment de camp per a estudiar l'efecte de la variabilitat espacial i temporal de l'aplicació de l'aigua sobre un conreu de panís regat amb una cobertura total d'aspersió (Capítol III). Es va utilitzar una cobertura típica dels nous desenvolupaments de reg de la vall de l'Ebre. Els resultats d'aquesta investigació mostraren que percentatges amplis de la variabilitat del CU i de les pèrdues d'aigua per evaporació i arrossegament podien ésser explicades per la velocitat del vent. No es van trobar evidències que provessin que el sòl disminueix l'heterogeneïtat introduïda per la distribució de l'aigua de reg. Els resultats indicaren que la variabilitat del rendiment del conreu va ésser dictada en bona mesura pel dèficit d'aigua degut a la no-uniformitat de la distribució de l'aigua durant el cicle del conreu. La làmina aplicada en els regs realitzats a partir de la floració del panís va estar significativament correlacionada amb el rendiment del conreu.

El desenvolupament d'un model de simulació que combina un model de conreus (Adror-Crop) i un model de reg per aspersió en cobertura total (Ador-Sprinkler) es va presentar al Capítol IV. Ador-Crop incorpora moltes de les característiques del model

CropWat. Però, s’han introduït millores substancials respecte el model original, com l’ús de temps tèrmic per al creixement dels conreus i la introducció de dades diàries de evapotranspiració de referència. Ador-Sprinkler aplica la teoria balística per a determinar la distribució d’aigua que resulta d’aspersors subjectes a un vector de vent. El model es va calibrar amb experiments de camp en dos marcs d’aspersió adjacents d’una cobertura equipada amb aspersors proveïts d’embocadures de 4,4 i 2,4 mm de diàmetre, disposats triangularment amb un espaiament de 18 x 15 m. Ador-Sprinkler va predir adequadament la distribució de l’aigua de reg durant tot el cicle del conreu. El model de conreus es va validar a través d’una comparació amb CropWat. Ambdós models van predir una reducció del rendiment similar. Respecte a la validació del model combinat, la representació dels valors mesurats i simulats d'aigua estacional disponible per al conreu davant la reducció de rendiment resultaren similars. El model combinat pogué explicar el 25 %** de la variabilitat de la reducció de rendiment mesurada.

Per últim, el model va ésser exploratòriament aplicat a un nombre de problemes de disseny i maneig del reg per aspersió (Capítol V). Els resultats més rellevants foren els que es van obtenir de la caracterització de tècniques avançades de programació de regs. Les diferències en el rendiment del conreu i de l’ús de l’aigua derivades de regar a diferents hores del dia es van estimar en dues localitats amb importants diferències en la seva exposició al vent. En aquestes localitats es van desenvolupar corbes per a relacionar l’aigua usada amb el descens del rendiment dels conreus. La simulació es va aplicar també a l’estimació de valors llindars de vent per a un maneig òptim del reg. En la localitat més exposada al vent el llindar de 2.5 m s^{-1} resultà adequat per controlar la caiguda del rendiment i per minimitzar l’ús de l’aigua.

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INTRODUCCIÓN GENERAL

Introducción

El desarrollo de la agricultura de regadío ha ayudado a estabilizar y aumentar la producción de alimentos en muchas zonas del mundo. Mientras el regadío continua proporcionando importantes beneficios a la sociedad, también ha generado y aumentado problemas medioambientales. Efectivamente, las prácticas de manejo del agua de riego en muchos sistemas agrícolas han contribuido a la degradación de la calidad del agua superficial y subterránea, y a la salinidad de los suelos. Actualmente, la conservación del medio ambiente y la protección de los recursos naturales son objetivos tan importantes como la propia producción agrícola. Para ello, en el sector del regadío es preciso aumentar la eficiencia de riego, minimizar las pérdidas de agua que se producen en las conducciones y en parcela y controlar los solutos que aparecen en los retornos de riego.

En todos los sistemas de riego, un adecuado diseño y manejo permite hacer un uso más eficiente del agua disponible, maximizar la producción y limitar las pérdidas de agua por percolación profunda. Desafortunadamente, en muchas zonas regables del mundo la eficiencia de riego está por debajo de los niveles esperados (Clemmens y Dedrick, 1994). Estas bajas eficiencias pueden ser debidas a un déficit de agua y /o a un manejo inadecuado. Mientras se reconoce que es preciso mejorar el manejo del agua de riego para aumentar la sostenibilidad de la agricultura del regadío, los pasos necesarios para alcanzar este objetivo no están tan claros, debido a la complejidad de los sistemas de producción agraria.

Importancia del regadío en España y el valle medio del Ebro

El sector del regadío tiene una gran importancia en la política de desarrollo agrícola en España. En efecto, la transformación en regadío de tierras agrícolas fue la principal opción para aumentar la producción agrícola y contribuir al desarrollo económico del país durante el siglo XX. Así, la superficie regada, que representa solamente el 15 % de la superficie agrícola útil, aporta el 50 % de la producción agrícola nacional (Fereres, 1995).

En la cuenca del Ebro los regadíos tienen un nivel tecnológico diverso, ya que conviven sistemas tradicionales y sistemas modernos. El riego por superficie es el más frecuente en esta zona, y representa aproximadamente un 80 % de la superficie regada (Navarro, 2002b). En general, estos sistemas de riego se caracterizan por una eficiencia de riego baja. Entre los problemas típicos de estas zonas se incluyen los siguientes: 1) los sistemas de distribución tienen una capacidad inferior a la demanda punta; 2) la frecuencia del reparto del agua es rígida (es frecuente encontrar turnos de múltiplos de 24 horas); 3) las parcelas están mal niveladas; 4) el sistema de distribución está muy ramificado; y 5) las parcelas son de tamaño pequeño (Faci et al., 2000; Playán et al., 2000). En el análisis de una zona regable representativa de los regadíos tradicionales de riego por superficie en la cuenca media del Ebro (Bensaci, 1996; Slatni 1996), se propusieron esquemas de modernización basados en la mejora de la estructura de la red de distribución y en la mejora de la eficiencia de riego en parcela (mejorando el riego por superficie y/o cambiándolo a aspersión). Estos nuevos sistemas de riego tienen la capacidad, cuando están bien diseñados y gestionados, de alcanzar un alto nivel de eficiencia.

Actualmente, el Gobierno de España está comenzando a ejecutar un programa para modernizar muchas zonas regables con la colaboración de las comunidades autónomas (Forteza del Rey, 2002). Al mismo tiempo, se están realizando inversiones publicas y privadas para poner en marcha nuevos regadíos con sistemas de riego a presión (aspersión y goteo) (Navarro, 2002a). Estos sistemas tienen algunas ventajas sobre el riego por superficie. Así, el riego por aspersión se puede adaptar a una gran variedad de cultivos, aplicando riegos frecuentes y en una gama amplia de condiciones topográficas y características de suelos. También puede ser parcial o totalmente automatizado para minimizar el coste de la mano de obra y aplicar una programación de riego adecuada. Dentro del riego por aspersión, en el valle del Ebro resultan muy frecuentes los sistemas de cobertura total, ya que las parcelas con frecuencia no tienen las dimensiones necesarias para que los pivotes o las máquinas de desplazamiento lateral resulten económicas.

En España la información referente a la calidad del riego de los sistemas modernos de riego es escasa. Por ello, la evaluación de la calidad del riego en estos regadíos es una tarea importante para mejorar la gestión del agua y preservar la calidad medio ambiental.

Tecnología del riego por aspersión

En las últimas décadas, se han sucedido muchas mejoras en la tecnología del riego por aspersión (Tarjuelo, 1994a). Los cambios han permitido mejorar la calidad del riego, disminuir las pérdidas de agua y aumentar el rendimiento de los cultivos. En el ámbito del riego por cobertura total, los sistemas actuales en el valle del Ebro se basan en el uso de redes colectivas que garantizan a los regantes individuales un conjunto de condiciones de acceso al agua de los hidrantes. Entre estas condiciones se encuentran unos mínimos de presión y caudal. A partir de este punto los agricultores instalan sus equipos de fertirriego, automatización riego en parcela. Los equipos de fertirriego se han convertido en compañeros frecuentes de los sistemas de riego presurizado, que permiten una adecuada aplicación de los fertilizantes (e incluso fitosanitarios) disueltos en el agua de riego.

La automatización del riego, que dio sus primeros pasos en el valle del Ebro en la década de los años 80, se ha convertido en un complemento indispensable de las nuevas instalaciones y en una carencia relevante de las instalaciones más antiguas. Los programadores del riego por aspersión son en la actualidad robustos, potentes y baratos. En la actualidad, están apareciendo aplicaciones tecnológicas que pretenden avanzar en la automatización, y trasladar el control de la programación del riego de la parcela del agricultor a la oficina de la comunidad de regantes. Estos nuevos equipos, englobados en el nombre genérico del telecontrol de redes de riego se basan generalmente en una combinación de transmisión de datos por cable y radio, así como en técnicas de inteligencia distribuida, para lograr seguridad y eficacia en las transmisiones, así como para minimizar el efecto de las averías en cuanto a pérdida de información y costes de reparación. En cuanto al riego en parcela, los agricultores muestran preferencia hacia los sistemas que permiten un mayor grado de automatización: los pivotes y las coberturas totales.

La mejora de la tecnología en los pivotes se ha centrado en los aspersores. Se ha centrado en la sustitución de los aspersores por difusores, que tienen menores necesidades de presión y se adaptan a muchos suelos. Recientemente se han desarrollado nuevas generaciones de difusores, basados en platos deflectores rotatorios. Estos nuevos difusores pueden resultar importantes para mejorar la aplicación del agua en pivotes (Faci et al., 2001).

En las coberturas totales, los cambios se han centrado en la mejora de los marcos de aspersión. Si bien hace veinte años se instalaban coberturas en marcos triangulares con espaciamientos de 21 x 18 m, ahora resulta muy frecuente encontrar instalaciones nuevas con marcos triangulares en 18 x 18 m y en 18 x 15 m. El diámetro de las boquillas de riego también se ha reducido, y se ha pasado de diámetros superiores a 5,1 mm a los actuales de 4,0 o 4,4 mm. Los cambios han afectado también a otros aspectos de las coberturas, como el recorte de la longitud de las cañas, el material y diámetros de las tuberías enterradas, e incluso e material de los aspersores, ya que el plástico comienza a ser un material frecuente en el valle medio del Ebro.

Eficiencia y uniformidad del riego

La calidad del riego se ha venido estudiando tradicionalmente con índices de uniformidad y de eficiencia. Mientras la uniformidad cuantifica la variabilidad espacial de la distribución del agua, la eficiencia expresa el porcentaje del agua usada para riego que ha alcanzado el objetivo de contribuir a la producción agraria. Varios estudios se han centrado en la definición de parámetros que cuantifican la uniformidad y la eficiencia del riego (Merriam y Keller, 1978; Heermann, 1990; Clemmens y Dedrick, 1994; Burt et al., 1997). Estos parámetros han sido usados tradicionalmente como medidas del rendimiento del uso del agua en los regadíos. Los parámetros de calidad ponen el énfasis en los aspectos técnicos del manejo del agua. Otra medida alternativa de la calidad de riego es la eficiencia en la asignación del agua. Este concepto está más enfocado hacia la sostenibilidad económica del sistema, ya que estudia el coste de oportunidad de aplicar el agua a usos alternativos (Omezzine y Zaibet, 1998).

Las evaluaciones de riego en campo permiten diagnosticar la uniformidad del riego estableciendo niveles cuantitativos. Los sistemas de riego por aspersión requieren un valor mínimo de uniformidad para ser considerados aceptables. Para los sistemas de riego por aspersión, Keller y Bliesner (1990) clasifican la uniformidad de riego como "baja" cuando el Coeficiente de Uniformidad de Christiansen (*CU*) es inferior al 84 %. Por otro lado, la medida de la uniformidad en campo puede servir para calibrar modelos de simulación del riego por aspersión. Estos modelos permiten predecir la calidad del riego (generalmente uniformidad y eficiencia) basándose en las características físicas del sistema de riego, las variables de manejo del sistema y las condiciones ambientales. Estos modelos de simulación pueden ser muy importantes para mejorar los sistemas de riego actuales y para conseguir una elevada eficiencia en las futuras puestas en regadío

Efecto del viento sobre el riego por aspersión

El patrón de distribución de agua de los sistemas de aspersión se ve afectado por factores que dependen del diseño (como el marco de aspersión o el diámetro de las boquillas), del manejo (como la presión o la duración del riego) o de la meteorología (como la velocidad y dirección del viento). Distintos autores han mostrado que el viento es el factor ambiental con mayor efecto sobre la calidad del riego por aspersión (Faci y Bercero, 1991; Keller y Bliesner, 1990; Seginer et al., 1991; Tarjuelo et al., 1994a). De hecho, cuando se riega por aspersión con vientos de moderados a fuertes se produce un importante descenso de la uniformidad y un aumento de las pérdidas de agua por evaporación y arrastre. Todo esto puede reducir sensiblemente la dosis de riego efectiva.

El efecto del viento sobre la uniformidad del riego por aspersión ha sido estudiado por diversos autores y desde distintas perspectivas (Seginer et al., 1991; Tarjuelo et al., 1994b; Kincaid et al., 1996; Dechmi et al., 2000). Todos estos estudios han puesto de manifiesto que la uniformidad disminuye conforme aumenta la velocidad del viento. En el caso de los pivotes y las máquinas de desplazamiento lateral, el efecto negativo sobre la uniformidad no está tan claro, e incluso se ha documentado una cierta mejoría de la uniformidad en condiciones moderadas de viento (Faci et al., 2001).

La determinación de las pérdidas por evaporación y arrastre durante el riego por aspersión es compleja, al estar éstas afectadas por una gran cantidad de variables (Heermann et al., 1980; Edling, 1986; Silva y James, 1988). En muchos casos estas variables son difíciles de medir con precisión (Seginer et al., 1991). En experiencias con pluviómetros, las pérdidas se cuantifican entre el 2 % y 40 % (mayoritariamente entre el 10 y el 20 %), calculando éstas como el porcentaje del agua emitida por los aspersores que no llega a los pluviómetros respecto del agua emitida (Yazar, 1984). Diversos autores presentaron modelos empíricos que relacionan las pérdidas por evaporación y arrastre con las condiciones ambientales durante el riego (Frost y Schwalen, 1955; Yazar, 1984; Trimmer, 1987; Ortega et al., 1998; Montero, 1999; Tarjuelo et al., 2000).

En el valle del Ebro es frecuente que se produzcan vientos fuertes del NW-W, que se conocen como *"cierzo"* (Faci y Bercero, 1991). Debido a la importancia del riego por aspersión en Aragón y al efecto del viento sobre éste, se han desarrollado diversas ecuaciones para predecir las pérdidas por evaporación y arrastre en coberturas fijas y maquinas de riego (Faci y Bercero, 1991; Faci et al., 2001; Ramón, 1998). Las variables independientes que más frecuentemente se utilizan en las ecuaciones predictivas de las pérdidas de evaporación y arrastre son la velocidad del viento, la temperatura del aire, el déficit de saturación de la atmósfera y la presión de funcionamiento del aspersor.

Modelos de simulación de la distribución del agua de riego

Desde los años setenta se han venido utilizando modelos informáticos para el diseño y la gestión de sistemas de riego (Basset y Fritzsimmons, 1976; Clemmens, 1979; Strelkoff, 1970). Estos modelos se han venido aplicando al riego por superficie, debido a la intensidad de cálculo que precisa esta disciplina. En efecto, la complejidad hidráulica del riego por superficie hizo que desde el principio se pusiera énfasis en la simulación numérica como una vía para la mejora del uso del agua. Los modelos de simulación y diseño del riego por superficie se basan en la resolución de las ecuaciones flujo en aguas poco profundas por medio métodos de mayor o menor simplificación (Walker y Skogerboe, 1987). El desarrollo de los modelos de riego por superficie fue en buena medida paralelo al desarrollo de los ordenadores, y sus aplicaciones prácticas sufrieron un fuerte incremento con el desarrollo de las calculadoras programables primero y los ordenadores personales después. Si bien en la década de los setenta los modelos de riego por superficie se destinaron a aplicaciones académicas en ordenadores universitarios de uso restringido, a partir de 1980 aparecen los primeros modelos de diseño y simulación del riego por superficie destinados al uso por profesionales del riego. Entre ellos, destacaron los modelos de simulación SIRMOD (Walker, 1993) y SRFR (Clemmens y Strelkoff, 1999), que se complementaron con otros específicamente preparados para el diseño, como BASIN (Clemmens et al., 1993).

Mientras que todos estos desarrollos se producían en el riego por superficie, el riego por aspersión se consolidaba como una alternativa eficaz para el riego de muchos cultivos, y comenzaba su expansión territorial en el mundo. Sin embargo, el diseño del riego en parcela se basaba en criterios poco sólidos y se apoyaba en la experiencia local a la hora de encontrar la relación idónea entre el tipo de aspersor, el diámetro de las boquillas, la presión de funcionamiento, las condiciones de viento y el marco de aspersión. Otros aspectos, como la relación entre los tipos de suelo, su infiltración y la pluviometría del sistema o el diámetro medio de gota y su efecto sobre el encostramiento, quedaban igualmente a merced de la experiencia acumulada por los técnicos. Desarrollos informáticos como Catch3D (Allen, 1989) destinado al solapamiento matemático de las distribuciones experimentales de agua de aspersores aislados, formaron parte de las primeras aproximaciones a la utilización de herramientas informáticas en las instalaciones de riego por aspersión. Los modelos de simulación del riego por aspersión pueden ser herramientas muy importantes para mejorar los sistemas de riego actuales y para conseguir una elevada eficiencia en las futuras puestas en regadío.

Los primeros esfuerzos para la puesta a punto de modelos de diseño y simulación del riego por aspersión en coberturas totales se realizaron con aproximaciones balísticas (Fukui et al., 1980; von Bernuth y Gilley, 1984; Vories et al., 1987; von Bernuth, 1988; Seginer et al., 1991; Tarjuelo et al., 1994b). Este tipo de modelos se basa en la hipótesis de que un aspersor es una fuente de gotas de una distribución de diámetros conocida que vuelan hasta aterrizar siendo su trayectoria determinada por la presión en la boquilla y el viento. Los modelos balísticos tienen el inconveniente de que reproducen el riego en un marco concreto, ignorando la variabilidad de la presión en una parcela de riego. Su uso ha estado limitado hasta fechas recientes por la falta de modelos orientados a la aplicación por parte de técnicos de riego. En este momento, su principal limitación de uso reside en el complejo proceso de calibración a que está sujeto el uso de una determinada combinación de aspersor, boquillas y presión de funcionamiento. Recientemente, Carrión et al., 2001 y Montero et al., 2001 presentaron el modelo *SIRIAS* para la simulación del riego por aspersión en coberturas totales. Se trata de un modelo completo del riego, preparado para su aplicación práctica. Por otra parte, se está realizando avances en el desarrollo de los modelos de simulación de riego con pívot (Heermann, 1990; Bermond y Molle, 1995) y con cañones (Richards y Weatherhead, 1993; Augier, 1996).

La respuesta de los cultivos al agua y su relación con la uniformidad de riego

Varios trabajos han confirmado el impacto negativo de la falta de uniformidad de riego sobre el rendimiento de los cultivos y las pérdidas de agua por percolación profunda (Stern y Bresler, 1983; Dagan y Bresler, 1988; Or y Hanks, 1992). En el valle del Ebro (Cavero et al., 2001; Zapata y Playán, 2000; Zapata et al., 2000) analizaron el efecto de la uniformidad del riego por superficie sobre la variabilidad espacial de un cultivo de maíz, utilizando evaluaciones de campo, simulación de riegos y modelos de cultivos.

Cuando la uniformidad de riego es baja en las zonas del campo que reciben menos agua la producción se reducirá significativamente. Por otro lado, en las que acumulan excesos de agua se producirán importantes pérdidas por precolación profunda. Si bien ambos fenómenos pueden coexistir en una misma parcela, la relación entre la dosis media de riego y las necesidades de agua de los cultivos puede dar lugar a que prevalezca el déficit hídrico y por lo tanto la merma en la producción, o a que las pérdidas por precolación profunda sean muy importantes y con ello se consiga minimizar la caída del rendimiento. En un determinado sistema agrario, la relación entre el coste del agua y el valor de la producción determinará cuál es el fenómeno que prevalece. Por otro lado, el exceso de agua puede también inducir a un descenso del rendimiento a través de mecanismos como la pérdida de nutrientes.

Bruckler et al. (2000) resumieron un buen número de trabajos realizados sobre la uniformidad del riego y su relación con la producción de los cultivos. Estos autores concluyeron que la variabilidad de la humedad del suelo, la altura del cultivo y el rendimiento del cultivo tienen una estructura espacial similar a la de la distribución del agua de riego. Estos experimentos fueron generalmente diseñados para caracterizar el impacto de la variabilidad espacial del agua disponible en el suelo resultante de un riego no uniforme sobre el rendimiento. Sin embargo, no existen trabajos que estudien el efecto espacial y temporal del viento sobre el rendimiento de los cultivos a través de su efecto sobre la uniformidad del riego por aspersión. Este aspecto resulta muy importante para el diseño, manejo y evaluación económica de sistemas de riego por aspersión.

En la ultima década, numerosos modelos han sido desarrollados para simular el crecimiento de los cultivos y su balance de agua. Estos modelos ayudan a identificar los factores que controlan el rendimiento del cultivo y su evapotranspiración, así como a cuantificar su influencia. Dentro de los modelos de simulación de cultivos desarrollados hasta la actualidad, se puede distinguir entre los modelos que simulan los procesos del crecimiento del cultivo, tales como CERES-maize (Jones y Kiniry, 1986), CropSyst (Stockle et al, 1994), EPIC (Williams et al., 1984) y STICS (Brisson y Mary, 1996), y los modelos que han sido desarrollados para la programación del riego. Dentro de esta última categoría, CropWat (Smith, 1993) es el más conocido y utilizado. El modelo CropWat, a pesar de su relativa sencillez, ha sido aplicado con éxito a la simulación del efecto del estrés hídrico sobre el rendimiento de los cultivos (Frenken, 2000; George et al., 2000). En las condiciones del valle del Ebro, (Cavero et al., 2000) aplicaron los modelos CropWat y EPIC-phase a la simulación de experimentos de riego deficitario por superficie y aspersión en un cultivo de maíz.

Programas de mejora de la gestión del riego

En los sistemas agrícolas de riego, la disponibilidad del agua, su distribución y aplicación son frecuentemente factores limitantes de la producción. Estos factores contienen una mezcla de problemas técnicos, sociales y políticos. Por ello, las evaluaciones técnicas y económicas de los sistemas de riego no dan necesariamente soluciones factibles a los problemas del uso del agua. Determinar y definir estos problemas puede ser una tarea muy compleja. Por ello, el manejo del agua tiene que ser analizado en todos los contextos relacionados con el regadío.

El concepto de Programa de Mejora de la gestión (PMG) aplicado a sistemas agrícolas de regadío ha sido elaborado durante los últimos 20 años. Su objetivo principal es mejorar la calidad y la sostenibilidad de la agricultura de regadío en una zona. Según Dedrick et al. (2000), el proceso del PMG comprende: 1) profundizar en el conocimiento de la calidad de la agricultura de regadío en una zona (lo que en las condiciones de España a menudo coincide con una comunidad de regantes); 2) involucrar a los responsables del sistema en un proceso conjunto de toma de decisiones; y 3) ejecutar los cambios planificados. El PMG consiste en tres fases: 1) análisis y diagnostico; 2) planificación de la mejora de gestión y 3) implantación de las mejoras. En el polígono de riego y drenaje de Maricopa-Stanfield, situado en Proyecto de Arizona Central (EE.UU.), se aplicó un programa de demostración de mejora de la gestión en el año 1990 para evaluar su utilidad en la práctica. Definir un PMG es la mejor manera para identificar las fortalezas y debilidades de un determinado sistema de regadío (Dedrick et al., 1989).

Los PMG representan el contrapunto a los programas de mejora de las infraestructuras de riego que los agricultores y las administraciones públicas impulsan. Si bien la mejora de las infraestructuras en muy importante para conseguir una aceptable eficiencia de riego y la pervivencia de los sistemas agrícolas de regadío, resulta importante promover al mismo tiempo la mejora de la gestión para asegurar que las inversiones realizadas en infraestructura dan todo el rendimiento posible. Así, en muchos ámbitos, la mejora de la gestión, de una forma organizada y planificada es hoy por hoy un recurso muy poco explorado. Los PMG representan una oportunidad para que una comunidad de regantes comience un camino hacia la excelencia basado en la implantación de cambios graduales y endógenos. Los recursos necesarios para la mejora de la gestión son órdenes de magnitud inferiores a los necesarios para la mejora de las infraestructuras, y sin embargo, los resultados pueden ser muy importantes.

En el presente trabajo se aplicaron diversas metodologías para analizar los problemas del uso del agua en una comunidad de regantes de riego por aspersión, y se desarrolló una herramienta para estudiar con detalle el efecto del mayor problema del riego por aspersión en el valle del Ebro: el viento.

OBJETIVOS

En el marco de esta tesis se pretende contribuir a la mejora del uso del agua en el riego por aspersión. Para ello se adoptará una zona de estudio en la que se realizarán estudios conducentes a la puesta en marcha de un plan de mejora de la gestión del agua. Por otro lado, se realizará un ensayo de campo para establecer el efecto del viento sobre la uniformidad del riego y el rendimiento de un cultivo de maíz. Finalmente, se desarrollará un modelo combinado del riego por aspersión en cobertura total y del crecimiento de los cultivos. El modelo será calibrado y validado con el experimento de campo. Finalmente, se aplicará el modelo a la identificación de parámetros de diseño y particularmente manejo del riego por aspersión que permitan establecer relaciones entre el momento de aplicación del agua, el volumen de agua usada y el rendimiento de los cultivos. Los objetivos principales y subobjetivos de esta tesis doctoral son enumerados como siguiente:

Objetivo 1: **Analizar el uso del agua y la calidad del riego en la comunidad de regantes de la Loma de Quinto**. (Capítulos 1 y 2)

1.a. Caracterizar los sistemas de riego, los tipos de suelos y cultivos.

1.b. Evaluar la calidad del riego a través de la relación entre uso del agua y necesidades netas de los cultivos.

1.c. Identificar los aspectos que influyen en el uso del agua por parte de los agricultores.

1.d. Determinar la uniformidad de los principales sistemas de riego por aspersión: coberturas totales, pivotes y máquinas de desplazamiento lateral.

1.e. Validar un modelo balístico del riego por aspersión y aplicarlo a la estimación de la uniformidad de riego en las coberturas totales bajo diferentes condiciones de viento y presión de trabajo.

1.f. Simular el efecto de las prácticas de riego actuales y óptimas sobre el rendimiento de los cultivos y su margen bruto.

Objetivo 2. **Caracterizar el efecto del viento sobre el agua aplicada con el riego por aspersión y el rendimiento del maíz** (Capítulo 3).

2.a. Analizar la variabilidad de la aplicación de agua en cada riego y en el riego estacional.

2.b. Establecer la relación entre la variabilidad espacial del rendimiento de los cultivos y la variabilidad de la aplicación del agua y de las propiedades físicas del suelo.

Objetivo 3. **Desarrollar un modelo de simulación combinando un modelo balístico del riego por aspersión en cobertura total y un modelo de cultivos, y realizar una aplicación exploratoria a la mejora del diseño y particularmente del manejo del riego por aspersión en un cultivo de maíz** (Capítulos 4 y 5).

3.a. Formular, calibrar y validar un modelo de simulación del riego por aspersión en cobertura total de un cultivo de maíz.

3.b. Explorar el efecto del cambio de la orientación de las líneas de aspersión y del marco de riego sobre la calidad del riego y el rendimiento del cultivo.

3.c. Explorar el efecto sobre el uso del agua y el rendimiento de los cultivos de distintas estrategias de programación del riego basadas en la minimización del efecto negativo del viento.

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CHAPTER I

ANALYSIS OF AN IRRIGATION DISTRICT IN NORTHEASTERN SPAIN: I. CHARACTERISATION AND WATER USE ASSESSMENT

RESUMEN

En este trabajo se presenta la caracterización y evaluación del uso del agua en la comunidad de regantes de la Loma de Quinto (Zaragoza, España). El estudio se realizó para contribuir a la fase de análisis y diagnóstico de un programa de mejora de la gestión en esta comunidad de riego por aspersión. Los objetivos de este trabajo son: 1) caracterizar los sistemas de riego, tipos de suelo y cultivos; 2) evaluar la calidad del riego a través de la relación entre uso de agua y necesidades netas de riego; y 3) identificar los factores que afectan al uso del agua. Para alcanzar estos objetivos, se han realizado análisis estadísticos de datos de campo, de datos de la comunidad sobre la asignación del agua y de encuestas a los regantes. Se detectaron deficiencias técnicas en coberturas de riego, pivotes y máquinas de desplazamiento lateral. Un índice estacional de la calidad del riego (*IECR*), definido como el porcentaje de las necesidades netas de riego sobre el volumen estacional de agua facturada, se calculó en cada parcela para cada uno de los años de estudio. El *IECR* promedio alcanzó el 127 %, lo que indicó que los cultivos de Quinto sufrieron un estrés hídrico generalizado. Un análisis del *IECR* para los principales cultivos de la comunidad indicó que el estrés hídrico se aplicó de forma más intensa a los cultivos más resistentes al estrés y/o a los cultivos más subsidiados (el *IECR* para girasol fue de 142 %). El intervalo de riegos medio (12,3 días) y la dosis de riego media (44 mm) resultaron ser demasiado altos para algunos tipos de suelo de la comunidad. Los agricultores ajustaron el intervalo de riegos para acomodar el cambio de las necesidades de riego durante la temporada. La dosis de riego se redujo durante los días ventosos. En dos de los tres años de estudio, las parcelas grandes usaron menos agua que las pequeñas, a una tasa de aproximadamente - 5 mm. El elevado coste del agua en relación con el margen bruto de los cultivos, las deficiencias técnicas encontradas en los sistemas de riego, y las limitaciones impuestas por el clima y los suelos, resultaron ser las causas principales de los problemas de gestión de agua en la comunidad. En el segundo capitulo de esta serie, se presentan evaluaciones y simulaciones de riego. También se presentan y evalúan programaciones de riego para una producción óptima de los cultivos desarrolladas por simulación.

ABSTRACT

In this work, the Loma de Quinto irrigation district, located in Zaragoza (Spain) was characterised, and water use was assessed. The study was performed to contribute to the Diagnostic Analysis phase of an incipient Management Improvement Process in this sprinkler-irrigated district. The objectives of this chapter include: 1) characterizing the irrigation systems, soil types and crops; 2) evaluating irrigation performance through the relationship between on-farm water use and net irrigation requirements; and 3) identifying factors affecting on-farm water use. In order to accomplish these objectives, statistical analyses of field data, district records on water use and farmers' interviews were performed. Technical deficiencies were detected in solid-sets, centre-pivots and linear-moves. A Seasonal Irrigation Performance Index (*SIPI*), defined as the percentage of net irrigation requirements to seasonal water billing, was determined at each plot and for each of the three study years. The average interannual *SIPI* amounted to 127 %, indicating that crops in the district were consistently water stressed. An analysis of the *SIPI* for the main crops in the district revealed that water stress was more intense in drought resistant and/or heavily subsidized crops (*SIPI* for sunflower was 142 %). The average irrigation interval (12.3 days) and irrigation depth (44 mm) were too high for some of the soils in the district. Farmers adjusted the irrigation interval to meet the seasonal change in irrigation requirements. The irrigation depth was reduced in windy days. In two of the three study years, large plots used less water than small plots, at a rate of about -5 mm. The high cost of irrigation water in relation to crop revenues, the technical deficiencies of the irrigation systems, and the limitations imposed by climate and soils appeared to be major causes of local water management problems.

INTRODUCTION

In many irrigation projects around the world, water use efficiencies are below the expected levels (Clemmens and Dedrick, 1992). Low efficiency can be attributed to inadequate irrigation structures, poor on-farm management and/or insufficient water availability. Currently, farmers are confronted with severe economical and environmental pressures. In the European Union, the Common Agricultural Policy (CAP) seeks to ensure the sustainability of agricultural systems without creating surpluses. Agricultural products must become more competitive in markets that are increasingly open at the international level (de Juan et al., 1996). In this context, farmers must change their production systems so that water is considered not only as a limited resource, but also as a production factor and a relevant economic input.

A number of on-farm irrigation performance indexes have been defined (Merriam and Keller, 1978; Burt et al., 1997). These indexes quantify water management, and serve to identify problematic areas within an irrigated area. However, they do not inform on the reasons for the observed level of performance or provide guidance on how to improve it. Addressing performance problems is complex since improvement in farm water management must be viewed in the context of overall farm management. A Management Improvement Program (Dedrick et al., 1993; Dedrick et al., 2000) is an effective way to identify both the strengths and the weaknesses of irrigated agriculture.

The concept of Management Improvement Program (MIP) has evolved over the past 20 years. Its main objective is to improve the performance and sustainability of irrigated agriculture. According to Dedrick et al. (2000), the MIP process incorporates: 1) a thorough understanding of the performance of irrigated agriculture in an area; 2) involvement by key decision makers in a joint decision process; and 3) implementation of the planned changes by responsible operational managers. The MIP consists of three phases: diagnostic analysis, management planning and performance improvement. In the Maricopa-Stanfield Irrigation and Drainage District (MSIDD), located in central Arizona, an interorganizational demonstration management improvement program was implemented in 1990 to assess its usefulness in the evaluation of the performance management.

In the Ebro valley (Spain), irrigation districts have a varied technological level. Surface irrigation, using borders and level basins, is the most common irrigation method. In general, these irrigation systems are characterised by a low efficiency. Typical problems include: distribution systems with capacity below the peak demand; inflexible delivery rate and duration (usually in 24 hour shifts); and poor on-farm land levelling (Faci et al., 2000; Playán et al., 2000). These authors analysed a surface irrigated district representative of the Ebro valley: the Almudévar Irrigation District (AID). The study characterised the district's water management problems and evaluated modernisation scenarios. The authors concluded that the irrigation systems needed improvement and that the water distribution system was not able to provide a flexible and dependable water supply to the farmers. Consequently, they proposed a modernisation strategy based on the improvement of the conveyance structures and on conversion from surface to sprinkler irrigation. Currently, the Government of Spain is working on a program to modernise many irrigation districts. At the same time, public and private investments are being used to develop new irrigated areas using pressurised irrigation systems. These systems can attain irrigation efficiencies greater than 80 % if adequately designed and managed (Keller and Bliesner, 1990; Clemmens and Dedrick, 1994). Little information is available in Spain about the current levels of irrigation efficiency under sprinkler irrigation systems. Therefore, assessing irrigation performance in these modern districts is an important issue to improve water management and preserve the quality of the environment.

In chapter I and II, an analysis of water use and irrigation performance in the Loma de Quinto District (LQD) is presented. This analysis represents a contribution to the Diagnostic Analysis phase (Clyma and Lowdermilk, 1988; Dedrick et al, 2000) of an incipient MIP for the LQD. The next step will be to discuss this report in a multidisciplinary committee which will perform the Diagnostic Analysis not just on water issues, but on the current state of irrigated agriculture.

The objectives of chapter I include: 1) characterizing the irrigation systems, soil types and crops present in the LQD; 2) evaluating irrigation performance through the relationship between on-farm water use and net irrigation requirements; and 3) identifying factors affecting on-farm water use. In order to accomplish these objectives, statistical analyses of field data, district records on water use and farmers' interviews were performed.

THE STUDY AREA

The LQD was selected as the study area because farmers and district managers are interested in improving the profitability and sustainability of irrigated agriculture. From a technical point of view, the district is interesting because of the high cost of irrigation water (in comparison with crop revenues), the existence of water use records, the use of a wide variety of sprinkler irrigation systems, the limitations on irrigation operation imposed by the wind, and the variability in crops and soil types. The LQD is located about 40 km Southeast of Zaragoza, Spain (Figure I.1). The district is an extension of an old irrigation district, the Traditional Quinto District (TQD), which diverts water from the Ebro river. The TQD, consisting of about a thousand hectares of surface irrigated land, was the basis of the Quinto economy for centuries. Since 1987 farmers in Quinto cultivate the old irrigated area plus the sprinkler irrigated LQD. The LQD is located in a plateau about a 100 m above the TQD.

The LQD covers 2,606 ha, divided in 490 cadastral plots, and services 284 farmers (Lasierra, 1993). Each farmer cultivates a number of cadastral plots, which are usually spread throughout the district. Plot size varies between 0.2 and 71.8 ha. A variety of sprinkler irrigation systems (solid-set, centre-pivot and linear-move), are used to irrigate field crops (alfalfa, corn, sunflower and wheat). Fruit trees are produced in a few plots equipped with micro irrigation systems. District soils are shallow, have low organic matter, and are high in calcium carbonate and gypsum. The Quinto climate is semiarid, with an average annual rainfall of 266 mm and an average reference evapotranspiration (ET_0) of 1,243 mm. A relevant feature of the Quinto climate is the presence of an intense wind from the NW-W, locally called "*cierzo*". This wind produces large wind drift and evaporation losses and severely reduces irrigation uniformity in solid-sets (Faci and Bercero, 1991).

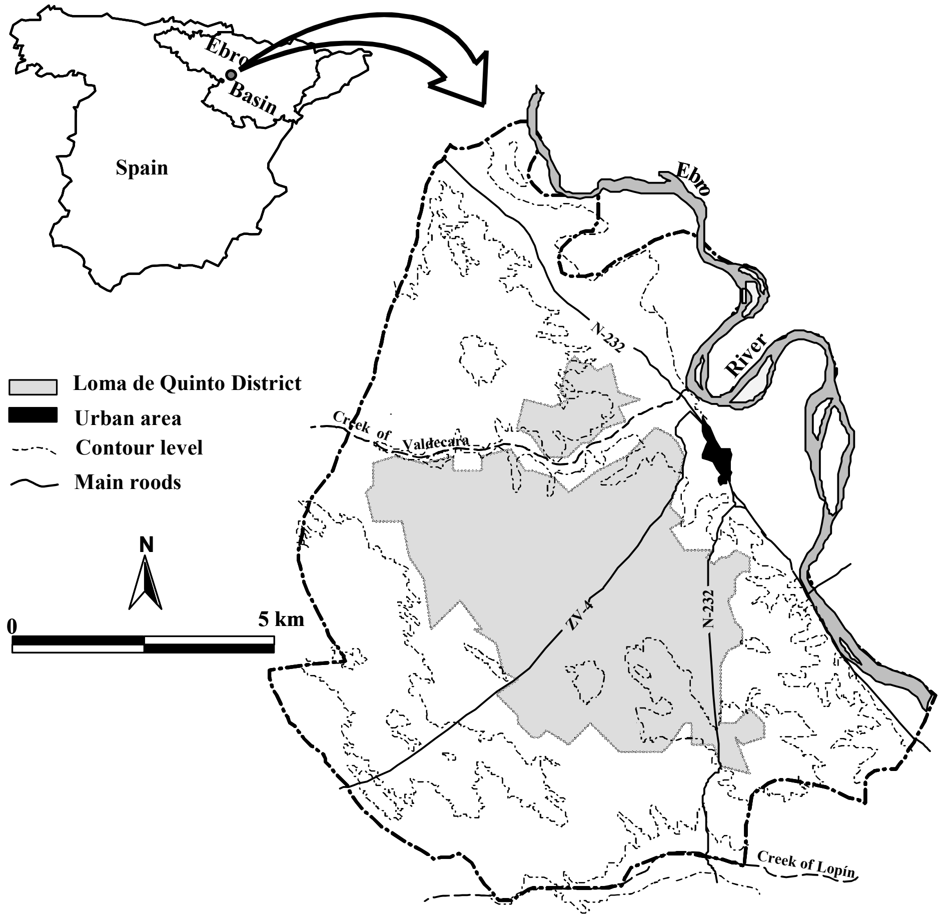

Figure I.1. *Location of the LQD*

Figura I.1. *Localización de la comunidad de regantes de la Loma de Quinto (LQD).*

Irrigation water is pumped from the Ebro River to a reservoir located at an elevation of 132 m. Due to the energy requirement, the cost of water (0.034 € m^{-3} in 1997) is very high in comparison with other districts of the Ebro basin growing field crops with surface irrigation (about 0.006 € m^{-3}). Water is supplied through a 60 km network of pressurised pipes. No additional pumping is required to convey water from the reservoir to the plots, although some farmers use booster pumps to increase the available pressure. All the hydrants are equipped with volumetric water meters. The distribution system is limited rate demand, as defined by Clemmens (1987).

The board of the LQD manages the district. The board is composed of district farmers, who are elected by fellow farmers, occupying the positions of president, financing administrator and consultants. The LQD hires personnel such as the secretary and a number of technicians to operate and maintain the pumping station, the irrigation network, and the reservoir.

MATERIALS AND METHODS

Temporal and spatial units of the study

The current level of irrigation management was analysed using records of irrigation practices for three different irrigation seasons, chosen according to their ET_0 (dry, average and humid) and to the availability of crop maps. The selected years were 1989, 1995 and 1997. The spatial unit of the study was the cadastral plot. This choice was dictated by the structure of the LQD management database and by the use of a geographic information system (GIS) containing cadastral information for mapping purposes.

Irrigation systems and cropping patterns

A 1997 field survey was used to prepare maps of district irrigation systems and crop spatial distribution (Dechmi et al., 1998). Farmers have not changed their irrigation systems since district operations began, so the same irrigation systems map was used for all three years of the study. Crop maps for the 1989 and 1995 irrigation seasons were obtained from Casterad (1990). In 1998, a field survey was conducted to collect LQD irrigation systems characteristics in each plot (Tejero, 1999). This information includes sprinkler spacing, sprinkler line azimuth, pivot or ranger length, nozzle(s) diameter(s), operating pressure and nozzle height.

District water records

Since farmers irrigate on demand, the district personnel does not take an active role in organizing water use. The district technicians write down all the water meter readings monthly, and the district secretary uses a computer database to store the readings, determine the volumes of water used and prepare a monthly water bill for each farmer.

Some hydrants supply water to a single farmer, while others are shared by a number of farmers. In the latter case, the secretary splits the cost of water according to the name, date and water volume recorded by the farmers themselves. A custom-made software is used to perform the database operations. This tool stores additional information, such as the size of the plots, the name and code of the owner, and the name of the irrigator

A general and a detailed study of water use in the district were conducted. In both cases we used information on water billing, and assumed that these volumes corresponded to actual water use. The technology applied in the LQD for water conveyance and measurement (pipes and water meters) makes this assumption much more reasonable than for districts using open ditches for water delivery, such as the AID (Faci et al., 2000). The general analysis examined the seasonal volume of water billed during the three years of study for entire district area. The detailed analysis focused on 17 plots (accounting for 44 ha), irrigated with solid-sets from 10 shared hydrants during the 1997 the irrigation season. These plots were selected because the individual irrigation dates and volumes were available at the district database. Alfalfa (10 plots), corn (4 plots) and wheat (3 plots) were grown on these plots.

Soils

Soil properties analysed in this study were soil depth (*p*, m) and total available water (*TAW*, mm). *TAW* was defined according to Walker and Skogerboe (1987), and computed after the following expression:

$$TAW = 10^3 p(\theta_{FC} - \theta_{WP}) \frac{\rho_b}{\rho_w}(1 - S) \qquad [1]$$

Where:

θ_{FC} = Gravimetric water content ratio at 0.03 Mpa (field capacity);

θ_{WP} = Gravimetric water content ratio at 1.50 MPa (wilting point);

ρ_b = Soil bulk density (Mg m^{-3});

ρ_w = Water density (Mg m^{-3});

S = Volumetric ratio of stoniness.

For the general study, the 19 soil units defined by Artieda (1998) in the Quinto soil map were grouped into five classes according to their *p* and *TAW* (Table I.1). For the 17 plots analysed in detail, *p* and *S* were determined *in situ*. Pressure plates were used to determine θ_{FC} and θ_{WP}, with two replicates per sample. In total, 39 samples were collected, using two or three samples per plot (characterising different soil horizons). ρ_b was set to 1.5 Mg m^{-3}, based on studies in the area (Artieda, 1998).

Table I.1. *Total available water [TAW], soil depth [p] and percent district area of the five soil classes.*

Tabla I.1. *Profundidad del suelo [p], agua total disponible [TAW] y porcentaje de la superficie de la comunidad de regantes para cada una de las cinco unidades de suelos.*

Soil class	S1	S2	S3	S4	S5
TAW (mm)	25	60 - 100	125 - 140	160 - 200	300
p (m)	0.30	0.60	0.80	1.00	1.20
Area (%)	19	37	33	5	6

Farmers interview

Farmers' water management and farming practices were analysed through an interview prepared and conducted in 1998. Twenty-one farmers were randomly selected for the interviews. The questionnaire consisted of 67 multiple choice questions about the farmer's irrigation systems and management practices. Other questions were devoted to establish if the farmers cultivated plots on lease and to compare irrigated agriculture in the LDQ and TQD (Tejero, 1999).

Net irrigation requirements

Irrigation requirements were estimated using the standard FAO procedures, as described by Doorenbos and Pruitt (1977) and Allen et al. (1998), and implemented in the CROPWAT software (Smith, 1993; Clarke et al., 1998). Following these procedures, Penman-Monteith reference evapotranspiration (*ET_0*), crop coefficients (*Kc*), crop evapotranspiration (*ETc*), effective precipitation (*PE*) and net irrigation requirements (*NIR*, mm) were estimated.

These estimations relied on mean monthly meteorological data recorded at the Quinto climatic station, located at a North latitude of 41º 25′ 25′′, a West longitude of 0º 30′ 30′′ and an altitude of 190 m. The data used included: maximum and minimum air temperature, maximum and minimum relative air humidity, precipitation, sunshine duration and wind speed. Missing minimum air humidity and sunshine duration data were replaced with data from the Zaragoza climatic station.

Duration of the crop development phases and primary crop coefficients (*Kc*) were obtained from Martinez-Cob et al. (1998). Monthly effective precipitation (*PE*) for 1989 and 1995 was determined using the USDA method (Cuenca, 1989). In view of the abnormally large rainfall recorded in 1997, *PE* for this season was calculated using the empirical method of effective precipitation (Smith, 1993). Net irrigation requirements were determined for the dominant crops (alfalfa, corn, sunflower and wheat).

Water use, irrigation efficiency and seasonal irrigation performance index

The performance measure used to characterise water use in the LQD was the Seasonal Irrigation Performance Index (*SIPI*), as defined by Faci et al. (2000) and applied to the AID. The *SIPI* is defined as the percentage of net irrigation requirements (*NIR*) to seasonal water use, estimated from billing records (*WU*, mm). *SIPI* represents a simplification of the irrigation efficiency standard concept defined by Burt et al. (1997), and Clemmens and Burt (1997). However, if a crop is water stressed, the value of the *SIPI* can be higher than 100 %. In fact, if the *SIPI* is higher than the potential application efficiency of the irrigation system, the crop will be water stressed.

Clemmens and Dedrick (1994) presented values of potential application efficiency for well designed and managed irrigation systems. Solid-sets range from 70-85 %, while pivots and rangers range from 75-90 %. We estimated an average value of potential application efficiency of 80 % for all irrigation systems in the district. This value was considered as a threshold separating full irrigation (*SIPI* < 80 %) from deficit irrigation (*SIPI* > 80 %). The *SIPI* was computed for each representative crop and year of the study.

Identifying factors affecting water use

Contingency tables were used to test possible interactions between the crops and three other categorical variables: type of irrigation system, type of farmer (owner or leaser) and soil *TAW* class. The goal of this analysis was to determine if these factors affected the choice of crop for each plot and study year.

Two types of correlation analyses were conducted for the detailed study. Their purpose was to gain insight on farmers' irrigation decision making, with particular reference to the main climatic limiting factor: wind speed. The first type of analysis involved data from individual irrigation events. The selected variables were: irrigation depth (mm), irrigation interval (days), wind speed (m s^{-1}) and date of each irrigation event (*DOY*, day of the year); The second type of analysis involved seasonal variables: the seasonal depth of water applied to each plot (mm), the average wind speed during the irrigation days (m s^{-1}), the average irrigation depth (mm), the average irrigation interval (days) and the *SIPI* (%).

Multiple regression with dummy variables was applied to study the interaction between quantitative and categorical variables in the general study, following the procedures used by Clemmens and Dedrick (1992) to analyse water use in the MSIDD. The dependant variables considered in this work were the seasonal water use and the *SIPI*. The plot area and the total area managed by the farmer in the LDQ were introduced as independent quantitative variables. These variables were included to assess the relationship between water use and land tenure, under the hypothesis that large plots or more professional farmers would promote water conservation. The independent categorical variables were the type of crop, the irrigation system, the soil class and the type of farmer (owner *vs.* leaser). The statistical model was developed by first including all the factors and then removing insignificant factors individually and iteratively.

RESULTS AND DISCUSSION

Characterization of irrigation systems, soils and crops

The spatial distribution of irrigation systems is depicted in Figure I.2. Solid-sets are used mainly in the North and Northeast areas, while centre-pivots and linear-moves are common in the Southwest, where plots are larger. This distribution can also be related to soil surface elevation, which is higher in the South. Higher pressures are available to operate the solid-set systems in the northern part of the LQD. The average area of solid-set plots is 4.0 ha. The most common sprinkler spacing is triangular, with sprinklers at every 21 m in the line and the lines separated 18 m. This spacing is used in 79 % of the total solid-set area. Most of the plots (54 %) are equipped with 5.1 and 2.4 mm diameter nozzles. The average operating pressure in the solid-set systems was 270 kPa. For similar hardware and operating conditions, Tarjuelo (1995) recommended an operating pressure in the range of 300-400 kPa, sensibly higher than the average observed value.

Figure I.2. *Map of irrigation systems in the LQD.*

Figura I.2. *Mapa de sistemas de riego en la comunidad de la Loma de Quinto (LQD).*

Solid-set uniformity can be severely reduced in the presence of strong winds. A common wind defence is to set the sprinkler lines perpendicular to the dominant winds (Keller and Bliesner 1990). In the case of triangular sprinkler spacings, this recommendation becomes more complicated, due to the fact that three possible sprinkler lines (forming angles of 60º) could be drawn around any given sprinkler (Figure I.3). In this particular case, the best protection against wind is an orientation with one of the lines (the horizontal line in Figure I.3) perpendicular to the wind direction. Therefore, the minimum angle between the dominant wind and a sprinkler line is 30º. In this case, the distance between sprinklers in a direction perpendicular to the wind is minimum, with a value of 10.5 m. As a result, the applied irrigation water attains a reasonable coverage of the soil. In the worst case one of the sprinkler lines is parallel to the wind direction. In this case the sprinkler spacing in the wind direction attains a maximum value of 18 m. This results in strips of non-irrigated land during windy irrigations.

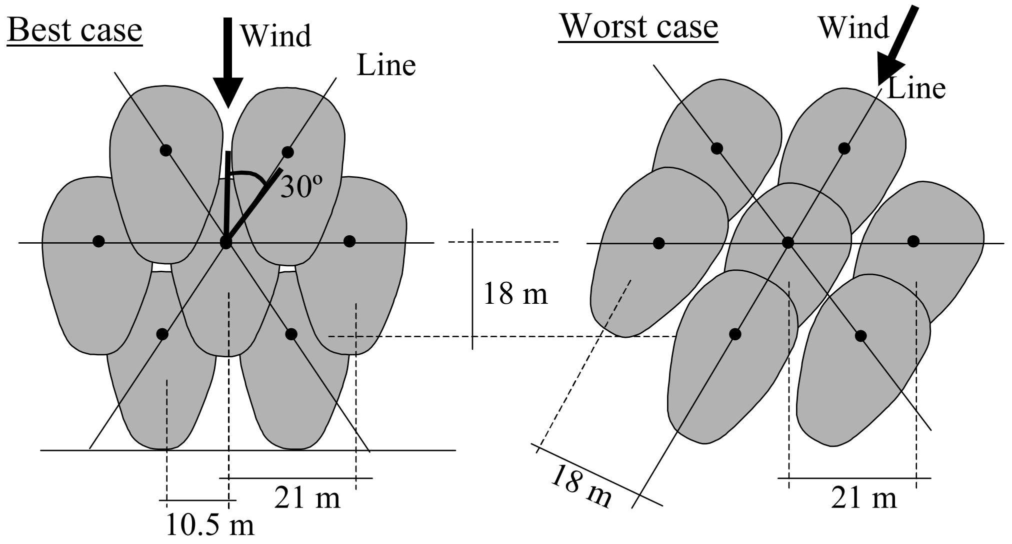

Figure I.3. *Representation of best and worst orientation cases between the wind and the sprinkler line for a triangular 21 by 18 m spacing. Dots represent sprinklers and ellipsoids represent the area wetted by each individual sprinkler.*

Figura I.3. *Representación de los casos mejores y peores de orientación entre el viento dominante y las líneas de aspersión para un marco triangular de 21 x 18 m. Los puntos representan los aspersores, mientras que los elipsoides representan al área mojada por cada aspersor individual.*

In order to assess the wind protection characteristics of the LQD solid-sets, plots were classified according to the sprinkler line azimuth. Considering the axes of symmetry in Figure I.3, Azimuths were reduced to an interval of 5º to 65º, divided in six 10º-intervals. Accordingly, the average wind Azimuth of 293º was reduced to an orientation of 53º (subtracting 240º). Figure I.4 confronts a histogram of the sprinkler line orientation groups with the dominant wind direction. The best sprinkler line orientation would be between 15º and 25º (approximately 30º angle with the dominant wind direction). Plots with optimally oriented lines represent 19.5 % of the total solid-set area (Figure I.4). In the LQD, 58.9 % of the sprinkler lines present adequate orientations (considered between 5 and 35º), suggesting that the design principle was only slightly considered. Additional wind protection could have been obtained at the design phase through a more careful sprinkler line orientation.

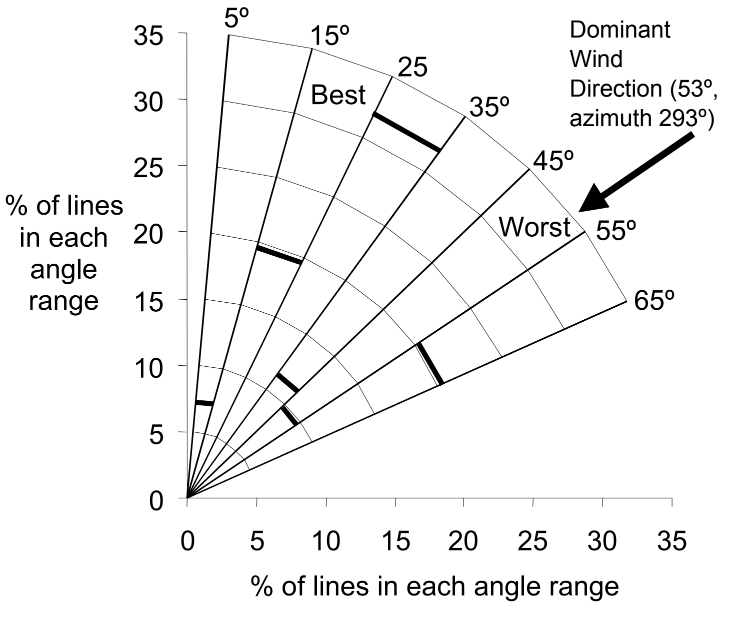

Figure I.4. *Histogram of sprinkler line orientation in LQD, with indication of the dominant wind direction.*

Figura I.4. *Histograma de orientación de las líneas de aspersión el la comunidad de regantes de la Loma de Quinto (LQD), con indicación de la dirección de viento dominante.*

The average area of the plots irrigated with centre-pivots is 13.6 ha. Centre-pivot systems are usually equipped with low pressure fixed spray plate sprinklers of different diameters located on top of the lateral, at 4.5 m over the soil surface. Recent developments in irrigation technology, such as rotating spray plate sprinklers (Faci et al., 2001) have not been introduced in the area. In 12 % of centre-pivots, farmers have lowered the nozzles in order to conserve irrigation water. In some cases, nozzles have only been lowered at the outer part of the centre-pivot. The average area of the plots irrigated with linear-move systems is 7.2 ha. These machines are also equipped with low pressure fixed plate spray sprinklers. In half of the linear-move machines the spray sprinklers are located at an elevation of 4.7 m over the soil surface. In the rest, the spray sprinklers have been lowered to an average height of 2.6 m.

A common trait of the LQD systems is the lack of irrigation automation. The interview revealed that 86 % of the farmers did not use any automation equipment, while the remaining 14 % used automation in some farms. The lack of automation devices poses a severe limitation to irrigation scheduling and to adapting the irrigation depth to the soil *TAW*.

Soils in the LQD show a large variation in water holding capability (Table I.1). Most soils (70 % of the area) have values of *TAW* ranging from 60 to 140 mm. Because of its low *TAW*, the S1 class shows relevant limitations for irrigation, and requires frequent, light irrigations. Soil classes S4 and S5 have a high *TAW* (160 to 300 mm) but are fine textured, saline and exhibit low infiltration and poor aeration. Therefore, they have low agronomic value.

Main crops in the LQD were wheat and corn in 1989, and alfalfa in 1995 and 1997 (Table I.2). The category "mixed crops" was relevant in the three years of study. It includes the plots in which farmers divide the total area to grow more than one crop at a time. This is a common practice in large plots.

Table I.2. *Crop distribution in the LQD during the study years.*

Tabla I.2. *Distribución de los cultivos en la comunidad de regantes de la Loma de Quinto durante los años de estudio.*

Crop	Area (%)		
	1989	1995	1997
Alfalfa and pasture	4.0	43.3	43.4
Corn	33.7	7.1	13.7
Sunflower	0.6	3.9	5.4
Wheat	35.7	8.4	10.6
Orchards	2.8	1.7	1.9
Vegetables	0.5	0.6	-
Industrial crops	-	2.8	-
Fallow	2.2	3.4	2.7
Mixed Crops	16.4	22.4	22.2
No data	4.1	6.5	0.1

Evaluation of irrigation performance

Seasonal water diversions in the LQD varied strongly during the study years. According to the pumping station records, the highest diversion occurred in 1995 (21.7 10^6 m^3), while in 1989 and 1997 diversions were much lower (10.9 10^6 m^3 and 13.2 10^6 m^3, respectively). The average *WU* was 477, 995 and 585 mm, for the 1989, 1995 and 1997 years, respectively. Table I.3 presents the distribution of the district plots in classes of *WU* for the three years of study. The variability in water application may reflect differences in crops, soils, irrigation systems and irrigation management. The effect of the crop on *WU* is illustrated in Table I.4. The associated coefficients of variation ranged from 27 to 63 %, indicating that additional factors determine *WU*.

Table I.3. *Percent distribution of the district plots in classes of seasonal water use [WU] for the three years of study.*

Tabla I.3. *Distribución porcentual de las parcelas catastrales de la comunidad en clases de uso del agua [WU] para los tres años de estudio.*

WU (mm)	Percentage of Plots		
	1989	1995	1997
< 500	31.1	21.5	42.9
500 – 700	15.9	8.8	27.4
700 – 900	8.8	16.9	21.3
900 – 1,100	10.4	21.1	4.0
1,100 – 1,300	13.2	13.7	2.3
> 1,300	20.7	18.1	2.1

Computed *SIPI* values for the studied crops suggest that farmers in the area regularly stress their crops (Table I.4). Only in one case (wheat in 1995) the average *SIPI* was lower than the estimated potential application efficiency (80 %). Sunflower was severely water stressed during all the study years, with an inter-annual average *SIPI* of 142 %. Alfalfa and wheat had average values of *SIPI* of 128 % and 113 %. The inter-annual average of the *SIPI* value for corn was 111 %, the lowest among all crops. These data suggest that farmers try to optimise irrigation water use restricting application on drought resistant crops (sunflower, wheat, alfalfa), and limiting water stress on drought sensitive crops (corn). The subsidies of the European Union play a relevant role in the *SIPI*. Subsidies are applied by the hectare, and amount to a variable percentage of each crop gross income. In the case of sunflower subsidies were comparatively high in the years of study, and therefore farmers did not consider yield as the main source of income. Consequently, sunflower was systematically under irrigated. Faci et al. (2000) reported a similar finding for the AID, based on data from 1994.

The district average *SIPI* (computed in all plots) was 155 %, 95 % and 131 % for the years 89, 95 and 97, respectively. These values indicate that the *SIPI* followed inter-annual trends that could not be explained by the aridity of the analysed years. Crop water stress was considerable during the years 1989 and 1997. In 1995, which was considered as an average year with an average evaporative demand, the seasonal amount of irrigation water applied to alfalfa, corn and wheat was higher than their net irrigation requirements.

Table I.4. *Net irrigation requirements [NIR], water use [WU] and Seasonal Irrigation Performance Index [SIPI] of the main crops in the 1989, 1995 and 1997 irrigation seasons. Coefficients of variation for WU and SIPI are included in parenthesis.*

Tabla I.4. *Necesidades de riego netas [NIR], uso del agua [WU] e índice estacional de la calidad del riego [SIPI] para los principales cultivos en las campañas de riego de 1989, 1995 y 1997. Se incluyen en paréntesis los coeficientes de variación de WU y SIPI.*

	Alfalfa			Corn			Sunflower			Wheat		
	89	95	97	89	95	97	89	95	97	89	95	97
NIR (mm)	969	979	718	761	688	471	635	570	380	396	433	341
WU (mm)	773 (37)	1,163 (30)	693 (41)	600 (33)	813 (29)	602 (28)	592 (27)	719 (50)	270 (63)	338 (51)	762 (35)	434 (57)
SIPI (%)	150 (51)	92 (41)	141 (84)	152 (64)	91 (25)	89 (60)	118 (33)	126 (84)	181 (39)	150 (53)	71 (63)	117 (73)

A correlation analysis between the *SIPI* values obtained in the same plots in the three study years was performed. The purpose of this analysis was to assess how on-farm irrigation performance changed in the study years. Results showed a weak correlation between the *SIPI* values of years 89 and 95 (0.168*), with no significant correlation between years 89 and 97. However, there was a strongly significant correlation between the *SIPI* values of years 95 and 97 (0.484***). This finding suggests that on-farm irrigation performance has evolved during the life of the LQD. The criteria for water allocation in each plot were particularly consistent between 1995 and 1997, after almost ten years of irrigation operation.

Results from the detailed analysis showed that the average irrigation depth per irrigation event ranged from 18 to 73 mm, with an average of 44 mm and a CV of 30 %. This irrigation depth is compatible with the interview results: 60 % of the farmers use solid-set irrigation durations of 8 hours or more. The average irrigation interval varied from 8.6 to 28.0 days, with an average of 12.3 days and a CV of 40 %. These irrigation depths and intervals are too high for sprinkler irrigation in general and for the LQD soils in particular. The irrigation systems used in the district permit to apply frequent, light irrigations, at the only additional expense of labour or automation equipment.

The previous results state that farmers under irrigate their crops in the LQD. The interview included a few questions on this topic, formulated as a comparison between water use in the LQD and the TQD. 43 % of the farmers used “more water” in the TQD than in the LQD, while the remaining 57 % used “much more water”. 89 % of the farmers reported that crop yield was higher in the TQD than in the LQD. All of the interviewed farmers obtained higher profits in the TQD. Low seasonal irrigation depths, large irrigation intervals and poor soils seem sufficient to explain the low yields. The added factor of high water cost explains the reduced economic benefit in the LQD as compared to the TQD.

Identifying factors affecting water use

The first step was the analysis of contingency tables between categorical variables of the general analysis. Only in the first year of study (1989) a statistical relationship was found between crops and irrigation systems. Farmers did not grow alfalfa and sunflower in the plots equipped with irrigation machines (linear-move and pivot), using them for corn and wheat. This trend was discontinued in the following years. Both types of farmers (owners and leasers) grow the same crops in the LQD, and distribute them throughout the district area regardless of the soil types.

The second phase of the statistical study involved the analysis of correlation matrices established between the quantitative variables of the detailed study. First, the correlation analysis was performed on individual irrigation events (Table I.5). One of the most relevant characteristics of this table is that the correlation coefficients are low (below 0.3 in absolute value). This will be a constant in the rest of this study. The explanation for this fact lies in the nature of the data, which were obtained from the farmers' database. In our opinion, farmers have not been particularly careful in checking the accuracy of some variables. We believe that the water measurements are reliable, since water billing depends on these measurements and farmers use about one-fourth of their gross income to pay the water bill. Problems seem to accumulate in the estimation of the irrigated area. In some cases, not all the plot area was actually irrigated. In other cases, the water assigned to a plot seems to have been used to irrigate neighbouring plots owned by the same farmer. Our perception is that even if the farmers' database adequately allocates costs among farmers, it shows limitations when it comes to ensuring water traceability with respect to plots and crops.

A weak, negative correlation coefficient (r = -0.1411*) was found between irrigation depth and wind speed (Table I.5). In windy days farmers applied light irrigations, and seemed to wait for calm days to apply the gross of water requirements. The interview confirmed that this practice was followed by 70 % of the farmers. As an additional confirmation, the average wind speed in irrigation days (for all plots in the detailed study) was 0.92 m s^{-1}, whereas the average seasonal wind speed was 1.25 m s^{-1}. According to the farmers' interview, 95 %, 85 %, and 50 % of the farmers avoided irrigating in windy days with their solid-sets, pivots and rangers, respectively.

The irrigation depth (per irrigation event) was not related to the irrigation date (Table I.5), suggesting that farmers used fixed irrigation depths throughout the season, and met the irrigation requirements adjusting the irrigation interval. In fact, the irrigation interval showed a decrease in time during the irrigation season, reflecting the increased water demand during spring and mid summer. According to the interview, this procedure was followed by 76 % of the farmers. A significant, negative correlation between wind speed and irrigation date was found. Since the wind speed did not show a significant time dependence during the irrigation season (data not presented), it can be concluded that farmers became increasingly selective with the wind speed on irrigation days as the season progressed.

Table I.5. *Correlation matrix between the variables of each irrigation event in the detailed analysis.*

Tabla I.5. *Matriz de correlación entre las variables de cada riego en el análisis de detalle.*

	Irrigation Depth (mm)	Irrigation Interval (days)	Wind Speed (km h^{-1})	Date (-)
Irrigation depth (mm)		0.1360 *	-0.1411 *	0.0818 ns
Irrigation Interval (days)			0.0487 ns	-0.2753 ***
Wind Speed (Km h^{-1})				-0.2099 ***
Date (-)				

A second set of correlation analyses was performed using seasonal data from each plot of the detailed study. The correlation between seasonal water use and average irrigation interval (r = -0.5563*) serves to confirm part of the previous results: those farmers applying large seasonal irrigation depths used small irrigation intervals. The lack of correlation between seasonal water use and average irrigation depth confirms that the management variable was the number of irrigation events (and therefore the irrigation interval).

The last step of the statistical analysis consisted on formulating multiple regression models using dummy variables to incorporate categorical variables. Such models were first applied to explain the variability on *WU* (Table I.6). The plot area resulted significant in 1989 and 1997, with coefficients of -4.2 and -5.4 mm, suggesting that large plots have a potential to conserve water. The total area managed by the farmer and the type of farmer (owner *vs.* leaser) did not result significant in any of the three study years. Since management does not seem to be the key of a lower water use, the benefits of large plots seem to be due to a better irrigation technology. Clemmens and Dedrick (1992), when analysing the MSIDD, found that the area managed by the farmer was statistically relevant on water use, and determined a coefficient of about 1 mm, between four and five times smaller than the one reported in this research for plot size. In the MSIDD the type of farmer was also significantly related to water use. Faci et al. (2000), analysing the AID, identified a large dependence of water use on plot size, although they reported a number of administrative procedures increasing the volume of water billed to small farms.

The other factors affecting *WU* were the type of crop and the type of irrigation system. As expected, corn, sunflower and wheat used less water than alfalfa, although in some cases the contrast between alfalfa and corn and even sunflower was not significant. In 1995 and 1997 wheat and particularly sunflower showed a reduced water use. As for the irrigation systems, differences were not significant in 1989. In 1995 and 1997 the variable was significant, solid-sets were the systems using most water, and only one contrast was significant in each year (linear-move in 1995 and hand move in 1997). In a context of increasing labour scarcity, hand move systems showed small water use, and were associated to marginal plots.

Table I.6. *Results of the multiple regression with dummy variables used to characterise the factors affecting water use [WU] in the years of study.*

Tabla I.6. *Resultados de la regresión lineal múltiple con variables dummy utilizada para caracterizar los factores que afectaron al uso del agua [WU] en los años de estudio.*

Variable	Level	Coefficient (mm)		
		1989	1995	1997
Constant	-	889.4***	1267.9***	739.7***
Plot area (ha)	-	-4.2*	-	-5.4*
Crop	Alfalfa	0.0	0.0	0.0
	Corn	-245.6***	-207.9*	-86.1^{ns}
	Sunflower	-159.2^{ns}	-515.4***	-382.9***
	Wheat	-509.7***	-473.4***	-313.6***
Irrigation system	Solid-set	-	0.0	0.0
	Centre-Pivot	-	-26.8^{ns}	-7.7^{ns}
	Linear-move	-	-190.7*	-14.1^{ns}
	Hand-move	-	[†]	-612.7*

[†] In 1995 the plots equipped with hand move systems were excluded from the statistical analysis since their number was very low.

When multiple regression was used to explain the variability on the *SIPI*, the number of significant factors increased towards the end of the study period (Table I.7). In 1989, the *SIPI* could not be explained by any of the considered factors. In the 1995 irrigation season, crop type was the only significant variable, and sunflower was the only crop showing significant differences with alfalfa. Factors affecting the *SIPI* during the 1997 irrigation season were the type of crop, the irrigation system and the soil type. The statistical analysis showed that the corn *SIPI* values were 49 % smaller than the alfalfa *SIPI* values. The effect of the type of irrigation system only served to separate the hand move system from the rest of the systems. The relationship found between the soil type and the *SIPI* values indicated significant differences between low and average *TAW* values. The determination coefficients obtained in all the regression analyses performed for water use and *SIPI* were low (ranging between 7.7 % and 41.7 %). The quality of the data sources and the variability induced by irrigation farming operations are probable causes of this dispersion.

Table I.7. *Results of the multiple regression with dummy variables used to characterise the factors affecting the Seasonal Irrigation Performance Index [SIPI] in the study years.*

Tabla I.7. *Resultados de la regresión lineal múltiple con variables dummy utilizada para caracterizar los factores que afectaron al índice estacional de calidad de riego [SIPI] en los años de estudio.*

Variable	Level	Coefficient (%)		
		1989	1995	1997
Constant	-	-	93.3***	180.2***
Plot area (ha)	-	-	-	-
Crop	Alfalfa	-	0.0	0.0
	Corn	-	-14.0^{ns}	-49.4*
	Sunflower	-	71.1***	35.9^{ns}
	Wheat	-	10.9^{ns}	-6.4^{ns}
Irrigation system	Solid-set	-	-	0.0
	Centre-Pivot	-	-	3.6^{ns}
	Linear-move	-	-	8.2^{ns}
	Hand-move	-	-	504.0***
Soil type	S1	-	-	0.0
	S2	-	-	-53.7*
	S3	-	-	-55.8*
	S4	-	-	-41.6^{ns}
	S5	-	-	-22.2^{ns}

CONCLUSIONS

The analysis of irrigation water use during three irrigation seasons (dry, average and humid) was used to characterise the performance of relatively modern irrigation systems in the LQD. The following conclusions can be drawn from this analysis:

1. Most of the solid-set sprinkler systems in the LQD use wide sprinkler spacings (21 x 18 m). The current operating pressure is too low to ensure adequate water distribution. Additional wind protection could have been obtained through a narrower spacing and/or a more careful sprinkler line orientation.
2. Centre-pivot and linear-move irrigation machines use fixed spray plate sprinklers. Recent developments in sprinklers for irrigation machines have not been introduced in the LQD. In about one-third of the machines, sprinklers have been lowered (from about 4.7 m to 2.6 m) to improve water conservation.
3. Field crops are grown in the LQD (Alfalfa, corn, sunflower and wheat). The average *WU* was 477 mm in 1989, 995 mm in 1995 and 585 mm in 1997. This variability in water application could not be adequately explained by the aridity of the study years or the changes in the cropping pattern.
4. The average interannual *SIPI* was 127 %. Farmers regularly stressed their crops, particularly those characterised by their drought resistance and those receiving large subsidies applied by the hectare.
5. The average irrigation depth per irrigation event was 44 mm, and the seasonal average irrigation interval was 12.3 days. These values are too high, particularly for the soils characterised by a low *TAW*.
6. Farmers seem to respond to strong winds by applying light irrigations, and reserve large irrigation events for calm days. In general, farmers modify the irrigation interval rather than the depth in order to accommodate the irrigation schedule to the *NIR*.
7. Large plots used less water than small plots, at a rate of about -5 mm. Similar findings (but different rates) were reported in previous works on surface-irrigated districts (Clemmens and Dedrick, 1992; Faci et al., 2000).
8. Multiple regression models on *SIPI* became more complex along the three study years. In 1997 the significant dependent variables included the crop, type of irrigation system and soil type.

CONCLUSIONES

El análisis del uso del agua de riego durante tres campañas (seca, media y húmeda) fue utilizado para caracterizar la calidad del riego en los sistemas de riego de la comunidad de la Loma de Quinto. Estos sistemas son relativamente modernos. Del análisis aquí presentado se desprenden las siguientes conclusiones:

1. La mayoría de las coberturas de riego de Quinto usan marcos amplios (21 x 18 m). La presión de la red en las condiciones actuales es demasiado baja para asegurar una distribución correcta del agua de riego. Se podría haber conseguido una mayor protección contra el viento si se hubiera usado un marco más estrecho y/o si se hubiera elegido la orientación de las líneas más cuidadosamente.
2. Los pivotes y las máquinas de desplazamiento lateral distribuyen el agua con difusores fijos. Los recientes desarrollos en materia de difusores para pivotes no han sido introducidos en Quinto. En la tercera parte de las máquinas los difusores se han bajado para mejorar la conservación del agua (desde 4,7 m a 2,6 m, aproximadamente).
3. Los agricultores de Quinto desarrollan cultivos extensivos (alfalfa, maíz, girasol y trigo). El promedio de uso de agua fue de 477 mm en 1989, 995 mm en 1995 y 585 mm en 1997. Esta variabilidad en el uso del agua no pudo ser explicada adecuadamente ni por la aridez de cada año ni por los cambios en los cultivos.
4. El promedio interanual del índice estacional de calidad del riego (IECR) fue de 127 %. Los agricultores estresaron los cultivos de forma generalizada y de forma particular en el caso de cultivos caracterizados por su resistencia a la sequía o por recibir grandes subsidios aplicados por su superficie.
5. La dosis de riego media resultó ser de 44 mm, mientras que el intervalo de riegos medio estacional fue de 12,3 días. Estos valores resultan demasiado elevados, particularmente para los suelos que tienen una baja capacidad de retención de agua.
6. Los agricultores parecen responder a vientos fuertes aplicando riegos muy breves, y reservan los riegos copiosos para los días de calma. En general, los agricultores modifican el intervalo de riego y no la dosis de riego cuando intentan ajustar su calendario de riegos a las necesidades de agua de los cultivos.

7. Las parcelas más grandes usan menos agua que las pequeñas, en una relación e aproximadamente – 5 mm. Este mismo resultado (con una tasa diferente) fue descrito anteriormente en condiciones de riego por superficie (Clemmens y Dedrick, 1992; Faci et al., 2000).
8. Los modelos de regresión múltiple que explican el IECR resultaron ser más complejos a lo largo de los años de estudio. Así, en 1997, las variables independientes significativas incluyeron el cultivo, el tipo de sistema de riego y la unidad de suelos.

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NOTATION

The following symbols are used in this chapter:

AID = Almudévar Irrigation District;
DOY = day of the year;
ET_0 = reference evapotranspiration (mm);
ETc = crop evapotranspiration (mm);
Kc = crop coefficients ;
LQD = Loma de Quinto District;
MIP = Management Improvement Program;
MSIDD = Maricopa-Stanfield Irrigation and Drainage District;
NIR = net irrigation requirements (mm);
P = soil depth (m);
PE = effective precipitation (mm);
S = = volumetric ratio of stoniness (%);
SIPI = seasonal Irrigation Performance Index (%);
TAW = total available water (mm);
TQD = Traditional Quinto District;
WU = seasonal water use (mm);
θ_{FC} = gravimetric water content ratio at 0.03 Mpa (%);
θ_{WP} = gravimetric water content ratio at 1.50 Mpa (%);
ρ_b = soil bulk density (Mg m^{-3});
ρ_w = water density (Mg m^{-3}).

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CHAPTER II

ANALYSIS OF AN IRRIGATION DISTRICT IN NORTHEASTERN SPAIN: II. IRRIGATION EVALUATION, SIMULATION AND SCHEDULING

RESUMEN

En el capítulo I se caracterizó la comunidad de regantes de la Loma de Quinto, y se evaluó su uso del agua. En este trabajo se completa el estudio de esta comunidad con evaluaciones de riego, simulaciones de riego en coberturas de aspersión y programaciones de riego para un rendimiento óptimo de los cultivos. Los resultados de las evaluaciones de riego indicaron que el valor medio del coeficiente de uniformidad de Christiansen (*CU*) para coberturas, pivotes y máquinas de desplazamiento lateral fue del 68,0 %, 75,5 % y 80,0 %, respectivamente. En coberturas, el *CU* se redujo severamente con la velocidad del viento. Sin embargo, en pivotes y máquinas de desplazamiento lateral el *CU* resultó ser más elevado en evaluaciones con vientos de entre 2 y 6 m s^{-1} que en condiciones de calma. Las evaluaciones de campo se utilizaron para validar un modelo balístico de riego por aspersión en coberturas totales. Las variables de calidad del riego utilizadas para validar el modelo fueron el *CU* y la eficiencia potencial de aplicación del cuarto bajo. Ambas variables se pudieron predecir adecuadamente en el rango de las observaciones de campo. El modelo fue aplicado para extender los resultados de las evaluaciones de campo a todas las parcelas de Quinto con coberturas totales. Así se produjeron mapas de *CU* para diferentes velocidades de viento y presiones de funcionamiento. Estos mapas pueden ser usados para identificar parcelas con baja calidad del riego. El efecto de la programación del riego sobre el rendimiento de los cultivos y su margen bruto se analizó con ayuda del programa de simulación CropWat. La simulación de las prácticas de riego de 1997 en un número limitado de parcelas detectó que el riego deficitario y/o los largos intervalos de riego resultaron en una reducción del rendimiento el 12 %. La introducción de una programación de riego óptima (que elimina la reducción del rendimiento) implicaría que la dosis de riego estacional del alfalfa aumentara en 100 mm, y llevaría a la aplicación de riegos ligeros y frecuentes. Debido a la escasez de mano de obra en la Loma de Quinto, la implementación de esta programación óptima necesitaría un alto grado de automatización del riego, que hoy no está disponible. Considerando el valor del rendimiento adicional y los costes del agua de riego adicional y los equipos de automatización, el beneficio neto de la introducción de la programación óptima sería de unos 50 € ha^{-1}. El objetivo de este análisis es contribuir a la fase de análisis y diagnóstico de un incipiente programa de mejora de la gestión en la Loma de Quinto. Para completar esta fase, un comité multidisciplinar desarrollará un estudio no sólo sobre el riego, sino sobre el conjunto de la agricultura de riego en la Loma de Quinto.

ABSTRACT

In the first chapter, the Loma de Quinto Irrigation District (LQD) was characterized, and water use was assessed. In this work, the analysis of the LQD is completed with field irrigation evaluations, solid-set sprinkler irrigation simulations and irrigation scheduling for optimal crop yield. The results of the irrigation evaluations indicated that the average Christiansen Coefficient of Uniformity (*CU*) for solid-sets, centre-pivots and linear-moves was 68.0 %, 75.5 %, and 80.0%, respectively. In solid-sets *CU* was severely reduced by wind speed. However, in centre-pivots and linear-moves *CU* was higher in evaluations with wind speeds between 2 and 6 m s^{-1} than under calm conditions. The evaluation data set was used to validate a ballistic solid-set sprinkler irrigation simulation model. The performance variables used for model validation were *CU* and the Potential Application Efficiency of the Low Quarter. Both variables were adequately predicted in the range of the observed values. The model was used to extend the evaluation results to all the solid-set plots in the LQD. *CU* maps were produced for different wind speeds and operating pressures. These maps can be used to identify plots with low irrigation performance. The effect of irrigation scheduling on crop yield and net benefit was analysed using the CropWat simulation model. Simulations of the 1997 irrigation practices performed on a limited number of plots detected a 12 % decrease in crop yield due to deficit irrigation and/or large irrigation intervals. The introduction of an optimal irrigation schedule (avoiding yield reductions) would imply increasing the alfalfa seasonal irrigation depth by 100 mm, and applying light, frequent irrigation events. Due to

labour scarcity in the LQD, the implementation of the optimal schedule would require a high degree of irrigation automation, which is currently unavailable. Taking into consideration the value of the additional yield and the costs of the extra irrigation water depth and the automation devices, the resulting net benefit would be 50 € ha^{-1}. The purpose of this analysis of the LQD is to contribute to the Diagnostic Analysis phase of an incipient Management Improvement Program at the LQD. In order to complete this phase, an interdisciplinary committee will perform a study not just on irrigation but on a wide scope of irrigated agriculture in the LQD.

INTRODUCTION

A high uniformity is required to attain a satisfactory level of irrigation efficiency. Several uniformity measures have been proposed, with the Christiansen Coefficient of Uniformity (*CU*) being the most used for sprinkler irrigation (Merriam and Keller, 1978). A sprinkler water distribution pattern depends on system design parameters (such as sprinkler spacing, operating pressure, and nozzle diameter) and on environmental variables (wind speed and direction) (Keller and Bliesner, 1990). Wind speed affects not only uniformity, but also evaporation and wind drift losses. The Ebro valley is characterised by an intense wind from the NW-W direction, called "Cierzo". Due to the relevance of sprinkler irrigation in the valley, several empirical equations have been proposed for the estimation of wind drift and evaporation losses (Faci and Bercero, 1991; Ramón, 1998; Faci et al., 2001). The independent variables most commonly used in these equations are wind speed, air temperature and/or air humidity.

One of the standard practices to characterise water use in an irrigated area is to conduct irrigation evaluations. In sprinkler irrigation, the most valuable outcome of the evaluation process is irrigation uniformity. In the latest years, field evaluations have often been used to calibrate irrigation simulation models. The use of such models permits to estimate irrigation performance under untested operating and meteorological conditions and to extend the characterization of irrigation uniformity to untested plots. Irrigation simulation models can be used to improve irrigation performance, and therefore to save water and to increase farm profitability (Clemmens et al., 1999; Playán et al., 2000).

Several authors have simulated solid-set sprinkler irrigation water application using ballistic models (Fukui et al., 1980, Seginer et al., 1991, Tarjuelo et al., 1994, Carrión et al., 2001).

In the last decade, a number of computer models have been developed to simulate crop growth and soil water balance. Among them, the CropWat software (Smith, 1993; Clarke et al., 1998) was specifically designed to estimate net irrigation requirements, to develop irrigation schedules, and to assess the reduction in crop yield due to water stress in the different crop development stages. Crop models have proven useful to identify the factors controlling plant growth and water use (Cavero et al., 2000). Therefore, they can be used to link irrigation management practices to estimates of farm profitability.

The objectives of this chapter include: (1) Evaluate the uniformity of the main irrigation systems in the LQD: solid-sets, centre-pivots and linear-moves; (2) Calibrate a ballistic sprinkler irrigation model and apply it to the estimation of *CU* in the solid-sets of the LQD under different wind conditions and operating pressures; and (3) Simulate the effects of current and optimal irrigation management practices on crop yield and net benefit.

MATERIALS AND METHODS

Irrigation system evaluations

A total of 32 field evaluations of sprinkler irrigation systems were conducted in the LQD during 1987, 1988 and 1999, following the methodology described by Merriam and Keller (1978) and Merriam et al. (1980). 13 evaluations were performed in solid-set systems. In all cases, sprinklers formed a triangular layout. In 11 evaluations the sprinkler spacing was coded as T21x18. The “T” indicates triangular spacing, as opposed to rectangular (“R”), the first number indicates the spacing between sprinklers in a line (m) and the second number indicates the spacing between lines (m). As discussed in the chapter I, this sprinkler spacing is used in 79 % of the solid-set area in LQD. In the remaining two evaluations the spacing was T18x18, which is used in 12 % of the total solid-set area. In each evaluation, operating pressure, sprinkler discharge and water distribution were measured. A 3 m x 3 m square catch can network was set up within a sprinkler area to characterise water distribution. In two cases the test duration was selected by the farmers (6.0 hours, following their customary practices). In the rest of the cases, the experiment was shorter than a regular irrigation event (from 1.7 to 3.0 hours).

In centre-pivots and linear-moves 10 and 9 field evaluations were conducted, respectively. All the evaluated irrigation machines were manufactured by Valmont$^{\text{TM}}$ and were equipped with fixed spray plate sprinklers located 4.5 m over the soil surface, except for two linear-move machines with spray sprinklers at 1.0 and 2.0 m over the soil surface. In most of the evaluations it was not possible to measure the working pressure because manometers were not installed or were out of order. Catch cans were located along a line extending radially from the pivot point, and along a line parallel to the linear-move machine. In both cases 3 m spacing was chosen.

Wind speed was measured three times during each evaluation. Catch can data were used to calculate *CU* (Christiansen, 1942):

$$CU = \left(1 - \frac{\sum_{i=1}^{n} \left| d_i - \overline{d} \right|}{n\,\overline{d}} \right) 100 \qquad [1]$$

where:

$\overline{d}$ = Average precipitation collected in the catch cans (mm).
d_i = Precipitation collected at catch can number i (mm).
n = Total number of catch cans.

In centre-pivots catch can data was weighed according to the area represented by each catch can (Faci and Bercero, 1990).

In all evaluations the irrigation materials present in the field (often dating from 1987) were used. The effect of nozzle wear on irrigation uniformity was therefore included in the evaluation results, and could not be independently evaluated. Throughout the years, nozzle wear increases discharge and modifies water distribution (Ozkan et al., 1992).

Development, validation and application of a ballistic solid-set sprinkler irrigation simulation model

The reported solid-set irrigation evaluations results were used to validate a sprinkler irrigation model. The model uses ballistic theory to simulate the flight of water drops from the sprinkler nozzle to the soil surface. Model development followed the procedures reported by Fukui et al. (1980), Tarjuelo et al. (1994), Carrión et al. (2001) and Montero et al. (2001). Figure II.1 presents a functional diagram of the proposed simulation model. A solid-set sprinkler simulation proceeds as follows:

1. Obtain the drop size distribution curve corresponding to a combination of nozzle diameter (principal and auxiliary nozzles) and operating pressure. The empirical relations developed by Kincaid et al. (1996) were used.

2. Introduce in the model the empirical parameters *k1* and *k2* to adjust the coefficient of aerodynamic resistance as proposed by Tarjuelo et al., 1994, following Seginer et al. (1991). This adjustment has been shown to improve sprinkler irrigation simulation performance. The values of *k1* and *k2* proposed by Montero (1999) were used in this work.

3. Estimate wind drift and evaporation losses (*WDEL*, %). The equation used for this purpose was the one proposed by Faci and Bercero (1991) for the specific conditions of the LQD.

$$\mathrm{WDEL} = 20.44 + 2.70\ \mathrm{W} \qquad [2]$$

Where W is the wind speed (m s^{-1}). *WDEL* reduces the sprinkler discharge reaching the soil, and therefore the application depth.

4. Compute the trajectory of a single droplet of a given diameter, launched at given vertical and horizontal angles, and under a given wind speed and direction. The differential equations derived from ballistic theory are used for this purpose. The results of this phase are the coordinates of the droplet landing point.

5. Combine the landing point for drops of different diameters with the drop size distribution curve to obtain the spatial distribution of water application resulting from a single sprinkler.

6. Overlap the water application of a single sprinkler in accordance with the desired sprinkler spacing. The result of this phase is the spatial distribution of water application within a sprinkler overlap area. Simulated irrigation performance is evaluated dividing the sprinkler overlap area into a number of sub areas acting as catch cans. The catch can irrigation depth is computed for each sub area.

7. Determine the performance parameters *CU* and the potential application efficiency of the low quarter (PAE_{lq}). In determining PAE_{lq}, *WDEL* were considered as net water losses. Following Burt et al. (1997) *PAElq* was determined as:

$$PAE_{lq} = \left(\frac{\text{avg. depth of irrig. water contributing to target}}{\text{avg. depth of irrig. water applied such that } \mathrm{d_{lq}} = \text{target}} \right) 100 \qquad [3]$$

where d_{lq} is the low quarter irrigation depth.

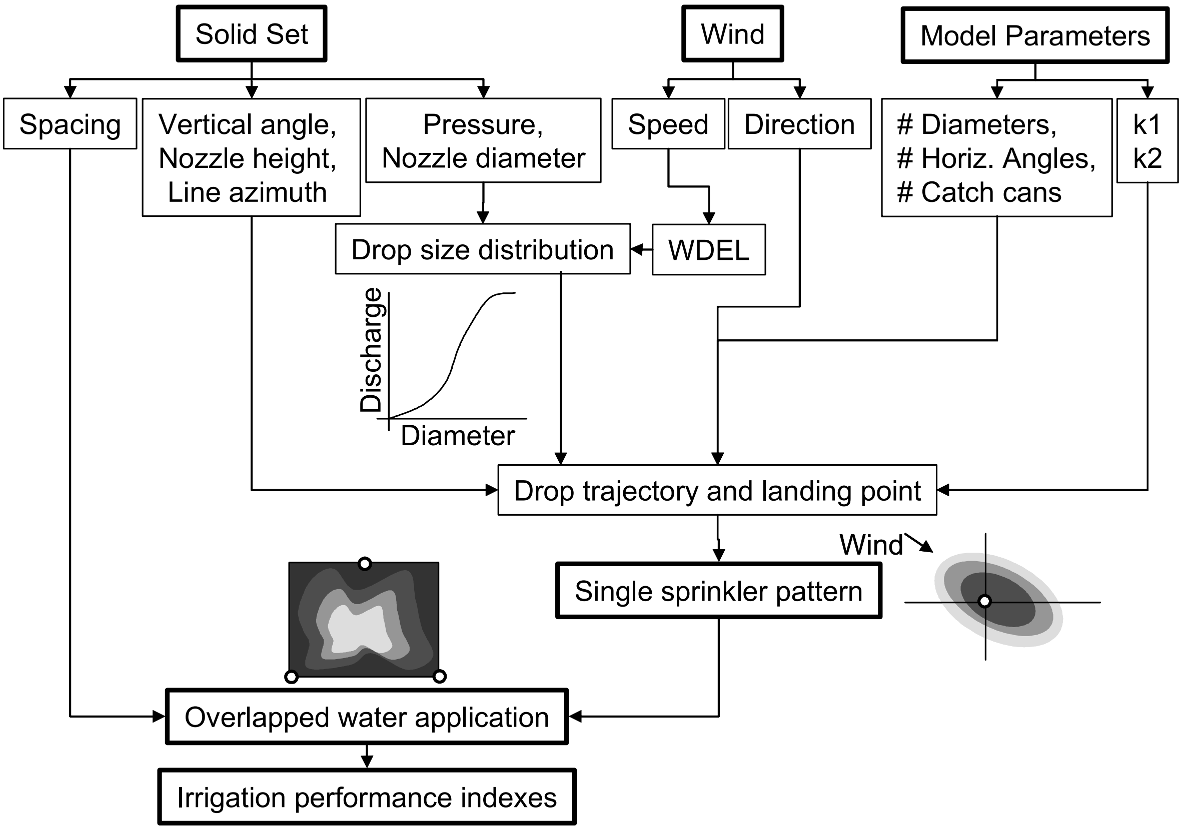

Figure II.1. *Functional diagram of the ballistic solid-set sprinkler irrigation simulation model.*

Figura II.1. *Diagrama funcional del modelo balístico de simulación del riego por aspersión en coberturas totales.*

Solid-set and weather data as well as model parameters constitute the input required for the simulation software. Regarding the solid-set, data include: diameter of the principal and auxiliary (if any) sprinkler nozzles, vertical angle of the sprinkler jet, nozzle height, operating pressure, azimuth of the sprinkler line and sprinkler spacing. Weather data include wind speed and direction. Model parameters include the number of drop diameters (180 diameters, ranging from 0.02 to 7.00 mm), the number of initial horizontal angles (180 angles, spaced 2º), the number of catch cans (324, distributed in a regular 18 x 18 network), and the values of *k1* and *k2*.

In order to verify the predictive capability of the model, the 13 solid-set field evaluations were simulated and field results were compared with simulation results using scatter plots and regression lines for CU and PAE_{lq}.

Once the model predictive capability was established, it was applied to simulate all plots in the LQD equipped with solid-sets. Different scenarios were produced combining variations in operating pressure and wind speed. The selected values for operating pressure were 200 kPa (low, inadequate, but not rare in the LQD), and 300 kPa (in the low range of adequate pressure, and just over the average pressure measured in chapter, 270 kPa). For wind speed, values of 1 m s^{-1} (very mild) and 3 m s^{-1} (common, moderate speed) were used. In the application of these four scenarios to the LQD, the inventory of sprinkler and solid-set characteristics reported by Tejero (1999) was used for each plot.

Simulation of irrigation scheduling and its effect on crop yield and net benefit

Since historical information on crop yield is not available in the LQD, irrigation scheduling simulation techniques were used to evaluate the influence of irrigation management on crop yield and water use in the LQD. The CropWat software (Smith, 1993; Clarke et al., 1998) was used to simulate current farmer management practices (irrigation dates and depths) and an optimal irrigation schedule (leading to potential yield). Simulation was applied to the 1997 irrigation season in the plots of the detailed analysis presented in chapter I.

Complete irrigation records were only available for 11 of the 17 plots included in the detailed analysis. Crops of these plots were alfalfa, corn and wheat. These plots were generally under-irrigated in the study year. We evaluated the increase in irrigation water use and crop yield derived from introducing an optimal irrigation scheduling. In the alfalfa plots we also evaluated the net benefit of optimizing irrigation management. The optimal yield of alfalfa hay was set to 15,000 kg ha^{-1} $year^{-1}$ (according to the farmers' experience), with a market value of 0.096 € kg^{-1}. The unit cost of irrigation water in the LQD was 0.034 € m^{-3}.

RESULTS AND DISCUSSION

Irrigation system evaluations

Table II.1 presents the results of the 13 irrigation evaluations performed in solid-set systems. Average *CU*'s are presented for classes of sprinkler spacing, operating pressure and wind speed. *CU* variability was large, ranging from 38.8 % to 88.1 %, with an average value of 68.0 %. For solid-sets, Keller and Bliesner (1990) considered this value relatively low (up to a threshold of 75 %). For the most common irrigation equipment in the LQD (T21x18 sprinkler spacing, 5.1 and 2.4 mm nozzles) and an adequate operating pressure (300 - 400 kPa, as discussed in chapter I), Ramón (1998) performed irrigation evaluations under controlled conditions. For wind speeds below 1.0 m s^{-1}, the resulting *CU* was 91.1 %. The average *CU* of a series of evaluations performed with wind speeds below 5.6 m s^{-1} was 86.1 %. Irrigation uniformity in the LQD seems to be limited by the use of single nozzles, inadequate pressure, nozzle wear and high wind speeds.

The highest *CU* value (88.1 %) was recorded in a 18x18 plot, with relatively low pressure (210 kPa), and wind speed of 2.8 m s^{-1}. Faci and Bercero (1991) found a threshold value of wind speed for solid-sets in the LQD of 2.1 m s^{-1} beyond which irrigation uniformity sharply decreased. This critical value is close to the wind speed recorded during the best-performing evaluation. These results suggest that the potential uniformity of the T18x18 spacing could be higher than recorded, particularly if the operating pressure was closer to 300 kPa and the wind speed was lower. The lowest value of *CU* (38.8 %) corresponds to a plot with a T21x18 spacing, a pressure of 280 kPa and a high wind speed (5.2 m s^{-1}). The large spacing and the high wind speed appear to be the main causes of this low *CU*.

Table II.1. *Summary of the main characteristics of the irrigation evaluations performed in solid-set systems.*

Tabla II.1. *Principales características de las evaluaciones de riego realizadas en las coberturas totales de aspersión.*

#	Sprinkler Spacing (m)	Operating Pressure (kPa)	Average Wind Speed (m s^{-1})	Nozzle Diameter(s) (mm)	Irrigation Duration (h)	CU (%)
1	T21x18	380	2.5	5.1	2.5	77.5
2	T21x18	430	0.3	5.1	2.0	76.4
3	T21x18	450	0.3	5.1	2.0	70.0
4	T21x18	450	11.7	5.1	2.4	72.5
5	T21x18	460	2.3	5.1	2.3	67.0
6	T21x18	460	5.8	5.1	2.6	50.3
7	T21x18	450	6.1	5.1	2.0	66.3
8	T21x18	460	5.5	5.1	1.7	48.9
9	T21x18	460	3.5	5.1	3.0	72.2
10	T21x18	280	5.2	4.4 and 2.2	2.1	38.8
11	T21x18	360	5.0	4.8 and 2.2	6.0	66.2
12	T18x18	220	1.4	5.1 and 2.2	2.0	86.5
13	T18x18	210	2.8	5.1 and 2.2	6.0	88.1
Spacing average	T18x18					87.3
	T21x18					64.5
Pressure average		< 300				71.1
		300 - 400				71.9
		> 400				65.8
Wind average			< 2.0			77.7
			> 2.0			65.1

When the sprinkler spacing is considered, the T18x18 spacing performed much better than the T21x18 spacing (*CU* = 87.3 %, 23 points higher than the average *CU*). The second considered factor affecting *CU* is the operating pressure. High pressures (over 400 kPa) resulted in lower values of *CU*. As expected, the average *CU* obtained with low wind speeds is higher than the one obtained with high wind speeds, with a difference of about 13 %. In some evaluations with the same spacing and pressure, similar values of *CU* were obtained independently of the wind speed (see evaluations 4 and 9 in Table II.1). These results suggest that *CU* may be affected by other wind-related factors, like the wind direction or the time variability of the wind speed and direction.

The effect of the irrigation duration can be illustrated by the two evaluations performed with a T18x18 spacing (evaluations 12 and 13, Table II.1). The most relevant difference between both evaluations is the irrigation duration (2 and 6 hours, respectively). A high *CU* was obtained in the long irrigation event (*CU* = 88.1 %) although the average wind speed was double than the wind speed measured during the short irrigation event. When the wind speed and direction are highly variable, as the irrigation duration increases the chances to obtain a high *CU* increase.

Table II.2 summarizes the 10 centre-pivot evaluations. 6 additional evaluations were conducted but not included in this table because both their operating pressure and wind speed were not available. However, they were considered in the determination of the average uniformity indexes. The average *CU* was 75.5 %. Only one evaluation presented a particularly low *CU* (58.6 %). In the rest of the evaluations, *CU* ranged from 70.4 % to 90.0 %.

Table II.2. *Summary of the main characteristics of the irrigation evaluations performed in centre-pivot sprinkler machines.*

Tabla II.2. *Principales características de las evaluaciones de riego realizadas en los pivotes.*

Evaluation #	Pivot Length (m)	Number of catch cans	Operating Pressure (kPa)	Wind Speed (m s^{-1})	CU (%)
1	280	60	220	1.4	70.4
2	280	60	220	-	90.0
3	280	60	220	-	73.9
4	340	52	260	3.5	86.1
5	208	39	280	1.3	73.1
6	208	39	280	0.8	83.6
7	195	65	-	2.6	85.5
8	204	68	-	1.7	58.6
9	141	47	-	0.5	77.0
10	159	53	-	3.3	76.6
Wind average				< 2.0	72.5
				> 2.0	82.7

“-“ indicates missing data

Table II.3 presents the results of 9 linear-move sprinkler evaluations. As with centre-pivots, 2 additional incomplete evaluations were not included in the Table, but their results were used to estimate average uniformity parameters. The average linear-move *CU* was 80 %. All the evaluations presented *CU*'s higher than the threshold established by Keller and Bliesner (1990) for "moderately low" uniformity (*CU* = 75 %), except for one case with *CU* = 50.7 %. In the linear-moves where farmers had lowered the spray nozzles from 4.5 m to 1.5 m, *CU* increased from 75.9 % to 83.8 %. Montero et al. (1999) – analysing pivot performance – did not find a significant effect of nozzle height on *CU*.

Table II.3. *Summary of the main characteristics of the irrigation evaluations performed in linear-move sprinkler machines.*

Tabla II.3. *Principales características de las evaluaciones de riego realizadas en las máquinas de desplazamiento lateral.*

Evaluation #	Linear-move length (m)	Number of catch cans	Operating Pressure (kPa)	Wind Speed (m s^{-1})	CU (%)
1	280	50	70	0.5	82.8
2	280	50	100	0.0	87.2
3	280	50	120	3.9	78.9
4	-	32	-	5.7	87.3
5	-	32	-	0.4	50.7
6	190	63	-	2.0	86.5
7	105	82	-	1.9	78.6
8	240	37	-	4.5	77.0
9	261	87	-	1.8	95.9
Wind average				< 2.0	79.1
				> 2.0	81.6

"-" indicates missing data

In the two types of machines, average *CU* was higher with a wind speed between 2 and 6 m s^{-1} than with wind speeds below 2 m s^{-1}. This can be explained by the findings of Faci et al. (2001), who reported that isolated fixed spray plate sprinklers apply most of the irrigation water in a circular crown. Inside the circular crown, the amount of irrigation water is minimum. Overlapping mathematically the distributions obtained with this type of nozzle, these authors found that mild and moderate winds could increase the *CU*. In previous experimental works, Hanson and Orloff (1996) observed similar results, while Hills and Barragán (1998) did not find and effect of moderate wind speeds on *CU*.

According to Cuenca (1989), the potential *CU* of centre-pivot and linear-move sprinkler machines is about 90 %. This value was reached in the LQD only in 8 % of the evaluations performed in the LQD. Adopting the current technology in sprinkler nozzles for irrigation machines and reducing the nozzle height would surely result in an increase in *CU* and a decrease in *WDEL*.

Validation and application of a ballistic solid-set sprinkler irrigation simulation model

The field evaluations performed in solid-set irrigation systems and reported in Table II.1 were simulated in order to provide a validation for the proposed ballistic model. Two evaluations were discarded for the validation of *CU*. These evaluations presented extreme wind speeds (over 6 m s^{-1}), beyond the range for which Faci and Bercero (1991) developed the *WDEL* predictive equation. Two additional evaluations were discarded for the PAE_{lq} validation, since the volume of water collected in the catch cans exceeded the applied irrigation depth. The comparison between measured and simulated values of *CU* and PAE_{lq} is presented in Figure II.2. Results show that the model predictive capability is better for PAE_{lq} (R^2 = 0.86***) than for *CU* (R^2 = 0.55**). In both cases the regression intercept did not differ from 0 and the slope did not differ from 1. Both performance parameters are adequately predicted in the range of observed values.

Improvements in the model predictive capability (particularly regarding *CU*) could be attained addressing three factors that will require a detailed study in the future. First, the proposed model uses time averaged wind speed and direction. Short-time variability of these variables during the irrigation event can have a relevant effect on the measured values of *CU* and PAE_{lq}. Second, a detailed model calibration will be required to estimate *k1* and *k2* for each combination of sprinkler manufacturer, nozzle diameter and operating pressure. Finally, the proposed model uses the equations presented by Kincaid et al. (1996) to determine the drop size distribution. Previous ballistic models derived this information from field experiments on the application pattern of isolated sprinklers, thus determining the drop size distribution fitting the model results to the experimental values for each combination of nozzle diameter(s), sprinkler manufacturer, and nozzle height.

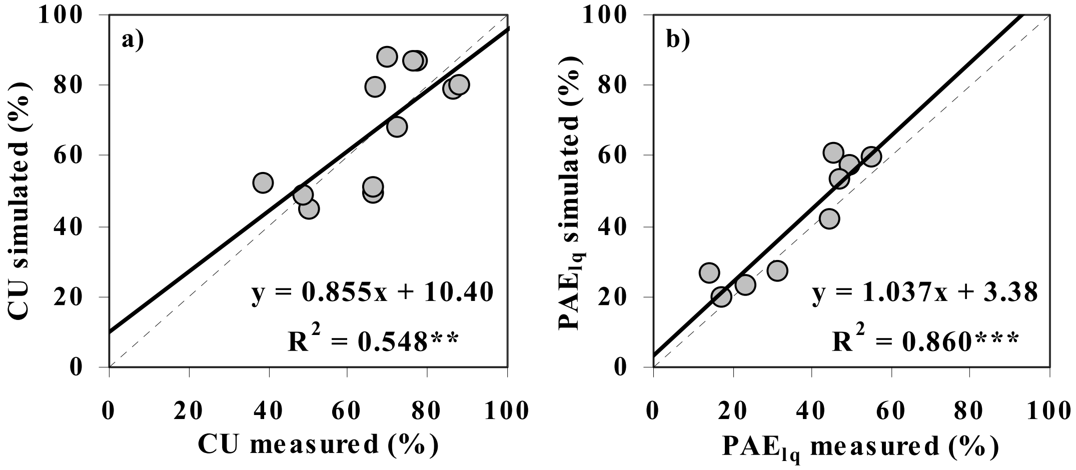

Figure II.2. *Linear regression between measured and simulated a) Christiansen Coefficient of Uniformity [CU]; and b) Potential Application Efficiency of the Low Quarter [PAE$_{lq}$].*

Figura II.2. *Regresión lineal entre los valores medidos y simulados de: a) el coeficiente de uniformidad de Christiansen [CU]; y b) la eficiencia potencial de aplicación del cuarto bajo [PAE$_{lq}$].*

Figure II.3a presents the average values of *CU* obtained with the simulation model in each solid-set LQD plot using combinations of two operating pressures (200 and 300 kPa) and two wind speeds (1 and 3 m s^{-1}). The maximum values of *CU* obtained in the different plots and sprinkler spacings correspond to the combination of adequate pressure and low wind speed. These simulated values of *CU* reached 84 % on the average. The plots equipped with the narrowest spacing (T15x15) also present high *CU* values with low pressure and mild wind and with adequate pressure and strong wind. The lowest *CU* values were observed in the plots equipped with the largest spacing (T21x18) except for the combination of low pressure and strong wind. In this case the average value of *CU* was higher than that obtained in the same conditions for narrower spacings, such as T18x15 and T18x18.

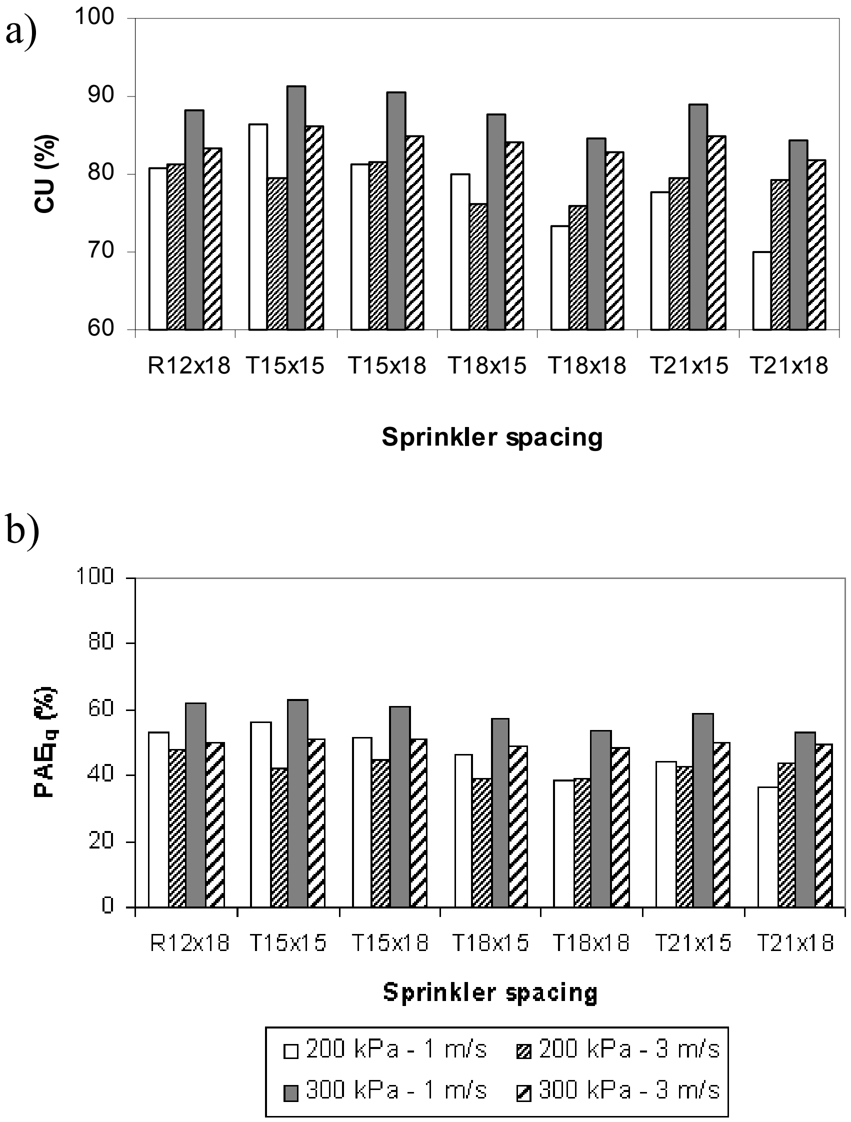

Figure II.3. *Average simulated CU (a) and PAE$_{lq}$ (b) values in the LQD for combinations of two operating pressures (200 and 300 kPa) and two wind speeds (1 and 3 m s^{-1}) Summarised by sprinkler spacing.*

Figura II.3. *Promedio de los valores simulados de CU (a) y PAE$_{lq}$ (b) en cada parcela de la comunidad de regantes de La Loma de Quinto, combinando dos presiones de trabajo (200 y 300 kPa) y dos velocidades de viento (1 y 3 m s^{-1}), ordenados por marco de aspersión.*

The dependence of PAE_{lq} on the sprinkler spacing, pressure and wind speed is similar to that found for *CU* (Figure II.3b). The most interesting result is that PAE_{lq} values are low, about 60 % in the best cases. This is partly due to the relevance of *WDEL* in the LQD. Faci and Bercero (1991) found that during the summer time, even in calm conditions, water losses amounted to 20 % of the applied water. On the other hand, individual irrigation PAE_{lq} values are often low because the spatial variability of the applied water is high. However, in sprinkler irrigation, most of this variability is associated to the wind speed, which has a strong random behaviour. Therefore, low PAE_{lq} values in individual irrigation events may be compatible with a high seasonal irrigation efficiency.

Figure II.4 presents the spatial distribution of simulated *CU* in the LQD solid-set plots with a pressure of 300 kPa, and wind speeds of 1 m s^{-1} (a) and 3 m s^{-1} (b). When the wind speed was low, 67 % of the solid-set area presented a *CU* higher than 84 %, the value recommended by Keller and Bliesner (1990) for this type of sprinkler systems. The rest of the plots presented *CU* values ranging between 78 % and 84 %. Under high wind conditions, most of the plots (82 % of the solid-set area), presented *CU* values below 84 %. The presented spatial analysis can be used to identify plots showing uniformity problems. These plots should be considered as primary targets of programs devoted to improve on-farm irrigation performance. The first step would be to confirm the model predictions with field irrigation evaluations.

Figure II.4. *Spatial distribution of simulated CU in the LQD solid-set plots for an operating pressure of 300 kPa and wind speeds of 1 m s^{-1} (a) and 3 m s^{-1} (b). Plots in white colour correspond to irrigation machines.*

Figura II.4. *Distribución especial del coeficiente de uniformidad simulado en las parcelas equipadas con cobertura fija en l a loma de Quinto de Ebro para una presión de 300 kPa y velocidad de viento de 1 m s^{-1} (a) y 3 m s^{-1} (b). Plots in white colour correspond to irrigation machines.*

Simulation of irrigation scheduling and its effect on crop yield and net benefit

Table II.4 presents the simulation of the current irrigation practices and the optimal irrigation schedule for the 11 considered plots. In the simulation of the current irrigation practices, the real irrigation dates and depths applied by the farmers were considered. Simulation results showed that the corn plot was the only one presenting a null yield reduction, with a moderate volume of deep percolation losses. In the rest of the plots crop yield reductions ranged from 9.6 % to 16.8 %. The optimal irrigation schedules developed for the 10 plots presenting yield reductions were characterised by larger seasonal irrigation depths and more irrigation events than the current farmers' practices.

Table II.4. *Simulated current and optimal irrigation schedule characteristics (seasonal irrigation depth [IDs]; number of irrigations [In]; Deep percolation losses [Dp] and yield reduction [YR]), and difference between the current and the optimal seasonal irrigation depths [DIDs] for the considered alfalfa, wheat and corn plots during the 1997 irrigation season.*

Tabla II.4. *Resultados de la simulación de las programaciones de riegos actual y óptima, (Dosis de riego estacional [IDs]; numero de riegos [In]; pérdidas por precolación profunda [Dp] y reducción de rendimiento [YR]) así como la diferencia entre las respectivas dosis de riego estacional [DIDs] para las parcelas consideradas de alfalfa, trigo y maíz durante la estación de riegos de 1997.*

Plot #	Crop	Current				Optimal		DIDs (mm)
		IDs (mm)	In (-)	Dp (mm)	YR (%)	IDs (mm)	n (-)	
1	Alfalfa	509	18	39	17	736	23	227
2	Alfalfa	682	18	128	10	729	27	47
3	Alfalfa	713	18	134	11	729	27	16
4	Alfalfa	737	20	160	10	750	25	13
5	Alfalfa	706	20	136	11	750	25	44
6	Alfalfa	723	19	180	13	750	25	27
7	Alfalfa	580	15	98	12	759	23	179
8	Alfalfa	505	13	61	13	759	23	254
9	Wheat	113	2	0	17	315	7	202
10	Wheat	302	8	35	16	350	10	48
11	Corn	506	16	58	0	-	-	-

The difference between the current and the optimal seasonal irrigation depths was relevant for plots 1, 7, 8 and 9. In these plots, large additional amounts of irrigation water were required in the optimal schedule to eliminate yield reduction. The rest of the plots presented moderate differences in the seasonal water application, and the elimination of yield reduction was obtained via a considerable reduction in the deep percolation losses. Farmers' irrigation in these plots was not properly scheduled in terms of timing and depth, and the soil water holding properties were not taken into consideration. In all these cases, the optimal schedule resulted in an increase in the number of irrigation events (7 additional irrigations on the average) and in a decrease on the irrigation depth per irrigation event.

An estimation of the additional yield and additional water costs associated to the introduction of the optimal irrigation schedule in the alfalfa plots is presented in Table II.5. The average gross irrigation depth should be increased from 644 mm to 745 mm. The difference between these benefits and costs resulted in an average additional income of 140 € ha^{-1}. A relevant factor has not yet been introduced in this simplified analysis: the labour required to perform the additional irrigation operations. According to the farmers' interview presented in chapter I, 86 % of the LQD farmers do not have irrigation automation devices. This is a relevant limitation to the introduction of the optimal irrigation schedule, since farmers will probably not adhere to an irrigation schedule requiring more manual operations and an accurate control of the irrigation timing. The generalization of on-farm automation devices in the LQD is the key factor for the implementation of the optimal irrigation schedule proposed in this article. Automating the irrigation systems in place in the LQD would require an investment equivalent to a yearly payment of about 90 € ha^{-1}. Including the irrigation automation cost, the net benefit of introducing an optimal irrigation schedule would be reduced to a moderate 50 € ha^{-1}. An additional benefit could be derived from a reduction of the current labour costs due to automation. However, in the optimal schedule farmers would still have to check the proper functioning of the irrigation equipments, and therefore labour requirements would probably not be reduced by automation. The benefits of irrigation automation exceed the limits of the economic analysis, since automated operation is essential to the social sustainability of the LQD due to labour scarcity in rural Spain.

Table II.5. *Estimated value of the additional yield and additional water cost associated to the introduction of an optimal irrigation schedule in the considered alfalfa plots during the 1997 irrigation season.*

Tabla II.5. *Valor estimado del rendimiento adicional y del coste del agua adicional asociados a la introducción de una programación de riegos óptima en las parcelas consideradas de alfalfa durante la estación de riegos de 1997.*

Plot	Additional Yield (€ ha^{-1})	Additional Water Cost (€ ha^{-1})	Difference (€ ha^{-1})
1	241	78	163
2	145	18	127
3	157	6	151
4	138	6	132
5	169	12	157
6	193	12	181
7	175	60	115
8	181	84	97
Average	175	35	140

In their study of a surface irrigation district, Clemmens and Dedrick (1992) found that the irrigation depth presented an inverse, significant relationship with the level of irrigation management. In fact, farmers using scheduling techniques reduced their seasonal irrigation depth by 250 mm. In that case, irrigation scheduling was used to increase irrigation efficiency. In the LQD the problem is different: proper irrigation scheduling will allow farmers to obtain higher yields (approaching potential yields) with a moderate increase in water use.

CONCLUSIONS

In this chapter, the analysis has been extended to include irrigation evaluations, simulation of solid-set sprinkler irrigation and the relationship between irrigation scheduling and crop yield. The following conclusions can be drawn from this work:

1. The irrigation evaluations show that a number of factors affect irrigation uniformity in the LQD. Optimising these factors requires proper design (sprinkler spacing, nozzle selection) and an adequate selection of the operating conditions (pressure, irrigation duration or wind speed).
2. According to the solid-set system evaluations, *CU* in the LQD is low (68.0 % on the average). Irrigation uniformity seems to be limited by the use of large sprinkler spacings, single nozzles, inadequate pressure, nozzle wear and high wind speeds. In evaluations with low available pressure, narrow sprinkler spacings (T18x18) attained acceptable uniformity.
3. Linear-move irrigation machines and centre-pivots presented higher *CU* than solid-sets The average *CU*'s were 80.0 % for linear-moves and 75.5 % for centre-pivots. Uniformity was not severely affected by wind speed. A higher average *CU* was obtained with wind speed values between 2 and 6 m s^{-1} than under calm conditions.
4. The validation of the proposed ballistic solid-set sprinkler irrigation simulation model showed that the performance parameters *CU* and PAE_{lq} could be adequately predicted in the range of the observed values.
5. The ballistic model was used to extend the results of the irrigation evaluations to the entire district. *CU* maps were produced for different conditions of wind speed and operating pressure. These maps can be used to identify plots with poor irrigation performance. Field evaluations should be performed in these areas to confirm model estimations before introducing changes in irrigation design and/or management.
6. Crop yield simulation in a limited number of LQD plots in 1997 detected a water stress induced yield reduction of 12 % on the average. Water stress was caused by deficit irrigation and/or large irrigation intervals. Frequently, the water applied during each irrigation event exceeded the soil water holding capability, therefore resulting in presumably large deep percolation losses.
7. For the alfalfa plots, the application of an optimal irrigation scheduling detected the need to increase the seasonal number of irrigations and to decrease the irrigation depth per irrigation event. Such a policy would lead farmers to attain maximum crop yield at the expense of an additional irrigation depth of 100 mm. A simplified economic analysis revealed that the net benefit of introducing the optimal irrigation schedule (considering increased yield, water cost and irrigation automation cost) would be a moderate 50 € ha^{-1}.

In chapter I and II, an analysis of water use and irrigation performance in the LQD has been presented. The conclusions of this work could be extended to many similar irrigation districts of NE Spain and other areas of the world sharing similar irrigation technology, soils and climate. In order to complete the Diagnostic Analysis phase of the incipient Management Improvement Program at the LQD, an interdisciplinary committee will take up the task of confronting our findings with additional data and points of view on the current state of irrigated agriculture in the district.

CONCLUSIONES

En este capitulo, el análisis de la comunidad se ha extendido para incluir evaluaciones de riego, simulaciones del riego en coberturas totales de aspersión, y el estudio de la relación entre programación de riegos y rendimiento de los cultivos. Las siguientes conclusiones se pueden derivar de este trabajo:

1. Las evaluaciones de riego han mostrado que un buen número de factores influyen a la uniformidad del riego en la Loma de Quinto. La optimización de estos factores necesitará de un adecuado diseño de los sistemas de riego (marcos y boquillas), y de una cuidada selección de las condiciones en que se desarrolle el riego (presión de funcionamiento, duración el riego o velocidad del viento).
2. Los resultados de las evaluaciones de riego en coberturas indican que el CU en la Loma es bajo (68,0 % en promedio). La uniformidad del riego parece estar limitada por el uso de marcos de aspersión amplios, una única boquilla por aspersor, presiones inadecuadas, desgaste de las boquillas y elevadas velocidades del viento. En evaluaciones con bajas presiones, el uso de marcos de aspersión más estrechos (marcos triangulares de 18x18 m) mantuvo la uniformidad en el rango aceptable.
3. Las máquinas de riego de desplazamiento lateral y los pivotes presentaron una mayor uniformidad que las coberturas. El promedio de CU fue de 80,0 % para las máquinas laterales y de 75,4 % para los pivotes. La uniformidad no resultó significativamente afectada por la velocidad del viento. Se obtuvieron uniformidades mayores con velocidades de viento de entre 2 y 6 m s^{-1} que en condiciones de calma.

4. La validación del modelo balístico de riego por aspersión en coberturas totales mostró que los parámetros de calidad del riego (CU y la eficiencia potencial de aplicación del cuarto bajo) pudieron ser adecuadamente predichos en el rango de los valores observados.
5. El modelo balístico se usó para extender los resultados de las evaluaciones de riego a toda la comunidad. Se elaboraron mapas de CU para diferentes condiciones de viento y presión. Estos mapas pueden ser usados para identificar parcelas con baja calidad de riego. Para confirmar estas estimaciones se deberían realizar evaluaciones de campo en las parcelas seleccionadas antes de introducir cambios en su diseño y/o manejo.
6. La simulación del rendimiento de los cultivos en un número de parcelas de la comunidad sirvió para detectar una reducción del rendimiento debida al estrés hídrico de aproximadamente un 12 %. El estrés hídrico fue causado por un riego deficitario y/o por intervalos de riego demasiado largos. Con frecuencia el agua aplicada durante los riegos excedió la capacidad de retención del suelo, por lo que presumiblemente se producen en algunos casos perdidas relevantes de agua por precolación profunda.
7. En las parcelas de alfalfa, la aplicación de una programación óptima del riego sirvió para detectar la necesidad de incrementar el número estacional de riegos y disminuir la dosis de cada riego. Estos cambios harían que los agricultores obtuvieran la producción máxima, aunque deberían aportar 100 mm adicionales. Un análisis económico simplificado reveló que el beneficio neto derivado de la introducción de la programación de riego óptima (considerando el aumento en el rendimiento, el coste adicional del agua y los costes de automatismos) sería de unos moderados 50 € ha^{-1}.

En los capítulos I y II se ha presentado un análisis del uso del agua y la calidad del riego en la comunidad de regantes de la Loma de Quinto. Las conclusiones de este trabajo podrían ser hechas extensivas a muchas comunidades de regantes similares del nordeste de España y de otras áreas del mundo con similar tecnología de riego, suelos y clima. Para completar la fase de análisis y diagnóstico de un incipiente programa de mejora de la gestión en la Loma de Quinto, un comité interdisciplinar confrontará nuestros resultados con datos adicionales y puntos de vista acerca de la situación actual de la agricultura de regadío en la Comunidad de Regantes.

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NOTATION

The following symbols are used in this chapter:

CU = Christiansen Coefficient of Uniformity (%);
$\overline{d}$ = average precipitation collected in the catch cans (mm);
d_i = precipitation collected at catch can number i (mm);
Dp = deep percolation losses (mm);
IDs = seasonal irrigation dose (mm);
In = irrigations number;
$k1$ = empirical parameter;
$k2$ = empirical parameter;
LQD = Loma de Quinto District;
n = total number of catch cans;
PAE_{lq} = potential application efficiency of the low quarter (%);
$WDEL$ = wind drift and evaporation losses (%);
YR = yield reduction (%).

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CHAPTER III

WIND EFFECTS ON SOLID SET SPRINKLER IRRIGATION DEPTH AND CORN YIELD

RESUMEN

Se realizó un experimento de campo para estudiar el efecto de la variabilidad espacial y temporal de la aplicación del agua sobre un cultivo de maíz regado con una cobertura total de aspersión. Se utilizó una cobertura típica de los nuevos desarrollos de riego del valle del Ebro. Se realizaron distintos tipos de análisis para: 1) estudiar la variabilidad de la dosis de riego en cada riego y en el riego estacional; y 2) relacionar la variabilidad espacial del rendimiento con la variabilidad de la aplicación de agua y las propiedades físicas del suelo. Los resultados de esta investigación mostraron que porcentajes amplios de la variabilidad del coeficiente de uniformidad de Christiansen (*CU*) y de las pérdidas de agua por evaporación y arrastre podían ser explicados por la velocidad del viento. El riego estacional tuvo una elevada uniformidad (*CU* del 88 %), que resultó ser más alta que el promedio de la uniformidad de los riegos individuales (*CU* del 80 %). No se encontraron evidencias que prueben que el suelo disminuye la heterogeneidad introducida por la distribución del agua de riego. La uniformidad de la recarga de agua del suelo fue menos que la uniformidad del riego, y la relación entre ambas variables fue estadísticamente significativa. Los resultados indicaron que la variabilidad del rendimiento del cultivo fue dictada en parte por el déficit de agua debido a la no uniformidad de la distribución del agua durante el ciclo del cultivo. La uniformidad de los riegos aplicados a partir de la floración del maíz pudo ser significativamente correlacionada con el rendimiento del cultivo, lo que indica que en este periodo una selección adecuada de las condiciones de viento es necesaria si se quiere obtener un alto rendimiento en maíz regado por aspersión.

ABSTRACT

A field experiment was performed to study the effect of the space and time variability of water application on solid set sprinkler irrigated corn yield. A solid set sprinkler irrigation setup – typical of the new irrigation developments in the Ebro basin of Spain – was considered. Analyses were performed to (1) study the variability of the water application depth in each irrigation event and in the seasonal irrigation, and (2) relate the spatial variability in crop yield with the variability of the applied irrigation and with the soil physical properties. The results of this research showed that large percentages of the Christiansen coefficient of uniformity (*CU*) variability and the wind drift and evaporation losses were explained by the wind speed alone. The Seasonal irrigation had a high uniformity (*CU* of 88 %) and was higher than the average uniformity of the individual irrigation events (*CU* of 80 %). No evidence has been found proving that the soil diminishes the heterogeneity induced by the irrigation water distribution. The uniformity of soil water recharge was lower than the irrigation uniformity and the relationship between both variables was statistically significant. Results indicated that grain yield (*GY*) variability was partly dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season. The uniformity of the irrigation events applied beyond the flowering stage was correlated with grain yield, indicating that in this period a proper selection of the wind conditions is required in order to attain high yield in sprinkler irrigated corn.

INTRODUCTION

Two irrigation technologies are currently used for the irrigation of field crops, such as corn: surface and sprinkler irrigation. Several authors have reported on the advantages of sprinkler irrigation over surface irrigation (Cuenca, 1989; Fuentes-Yagüe, 1996). These advantages have led to a steady increase in sprinkler irrigation acreage during the last decades. For instance, according to the yearly survey of the Irrigation Journal, from 1985 to 2000 the percent acreage of sprinkler irrigation in the United Sates increased from 37 % to 50 %.

One of the most relevant parameters in the operation of sprinkler irrigation systems is the uniformity of water distribution (Merriam and Keller, 1978). Irrigation evaluations are used in the field to establish irrigation performance, which in sprinkler irrigation is primarily represented by irrigation uniformity. During the evaluation process, quantitative levels of uniformity are established. Sprinkler irrigation systems require a minimum value of uniformity in order to be considered acceptable. For solid set sprinkler systems, Keller and Bliesner (1991) classified irrigation uniformity as “low” when the Christiansen Coefficient of Uniformity (*CU*) is below 84 %.

Several authors have reported that wind is the main environmental factor affecting sprinkler performance (Seginer et al., 1991; Faci and Bercero, 1991; Tarjuelo et al., 1994; Kincaid et al., 1996; Dechmi et al., 2000). These references have led to two firm conclusions. First, part of applied water is lost by evaporation and – particularly – wind drift out of the irrigated area. Second, under windy conditions, the water distribution pattern of an isolated sprinkler is distorted and reduced. Therefore, the Coefficient of Uniformity shows a clear trend to decrease as wind speed increases. However, particular combinations of nozzle size, operating pressure and sprinkler spacing may show a slight increase in *CU* at low wind speeds (Dechmi et al., 2000).

The response of crop yield to irrigation water supply has been extensively analysed (Doorenbos and Kassam, 1979; Hanks, 1983). Several works have confirmed the negative impact of irrigation non-uniformity on crop yield and on deep percolation losses. Bruckler et al. (2000), summarizing previous research efforts, reported that the pattern of spatial variability in soil water, crop height and crop yield is often similar to that of the irrigation water application. A number of experiments were designed to characterise the impact of the spatial variability of the available soil water on crop yield (Stern and Bresler, 1983; Dagan and Bresler, 1988; Or and Hanks, 1992). A common conclusion of these studies is that besides water application variability, water dynamics in the vertical (deep percolation and capillary rise) and horizontal directions condition its availability at the crop root zone. Authors differ in the interpretation of the effects of the heterogeneity tied to soil properties on the water distribution in the profile: some consider that soil effects increase the irrigation water distribution heterogeneity (Sinai and Zaslavsky, 1977), while others consider that the soil diminishes the heterogeneity induced by the irrigation system (Hart, 1972; Stern and Bresler, 1983; Li, 1998).

No reference was found in the literature about the effect of the environmental factors (such as wind speed) on the time evolution of irrigation uniformity (during the irrigation season), and on the variability of crop yield within a solid set sprinkler spacing. This is a key issue for irrigation water conservation and for the proper design and management of solid set irrigation systems.

In the conditions of the Ebro valley of Spain, corn is one of the main irrigated crops. Current developments in new irrigation projects and in irrigation modernization are leading to a rapid increase in solid set sprinkler acreage. In the Ebro valley conditions, wind is a serious limiting factor to sprinkler irrigation, due to its high frequency and intensity (Hernández Navarro, 2002). In fact, more than 50 % of the daily average wind speeds registered in the irrigated areas of Aragón between April and September are higher than 2 m s^{-1} (Oficina del Regante, 2002). Crop water requirements for corn are among the largest in the area. This crop is very sensitive to water stress, particularly during the flowering stage. Relevant decreases in crop yield have been locally reported when the irrigation supply is limited (Cavero et al., 2000; Farré et al, 2000).

The purpose of this chapter is to evaluate experimentally the effect of irrigation water distribution under variable environmental conditions on corn yield in a solid set sprinkler irrigation setup typical of the new irrigation developments in the Ebro basin. Particular objectives include: a) to analyse the variability of the water application in each irrigation event and in the seasonal irrigation; and b) to relate the spatial variability in crop yield with the variability of applied irrigation and with the soil physical properties. The results of this research will serve two additional purposes: 1) to compare the magnitude of the variability and the derived relationships with those reported for a previous, similar experiment in the same area using surface irrigation; and 2) to establish a base for the calibration of sprinkler irrigation and crop simulation models. These models will be applied in future research to the exploration of alternative irrigation strategies.

MATERIAL AND METHODS

Experimental site

The experiment was conducted at the experimental farm of the Agricultural Research Service of the Government of Aragón in Zaragoza, Spain (41º 43´N, 0º48´W, 225 m of altitude). The climate is Mediterranean semiarid, with mean annual maximum and minimum daily air temperatures of 20.6ºC and 8.5ºC, respectively. The yearly average precipitation is 330 mm, and the yearly average reference evapotranspiration (*ETo*) is about 1,110 mm (Faci et al., 1994). The experimental soil was a Typic Xerofluvent coarse loam, mixed (calcareous), mesic, following the U.S Soil Survey Staff (1992) guidelines for soil classification and taxonomy. The P and K content in the upper 0.30 m soil layer was determined in a composite sample. The resulting values were 25.8 ppm of P and 194.0 ppm of K. The organic matter ranged from 1.4 % at the surface to 0.6 % at 1.5 m depth. The average pH was 8.2. Soil salinity levels (EC_e = 3.88 dS m^{-1} on the average) were found to be well above the threshold values for corn. Irrigation water is pumped from the Urdán canal, diverting water from the Gállego river (a tributary of the Ebro river). The Urdán water carries a relevant salt load (about 2 dS m^{-1}) during the summer. For this reason, the electrical conductivity of the irrigation water (EC_w) was monitored in each irrigation event.

Experimental design

The experimental design of the solid set sprinkler irrigation system was defined to obtain high irrigation uniformity under low wind speed conditions. The nozzle diameters were 4.4 mm (main) and 2.4 mm (auxiliary), and were located at a height of 2.30 m over the soil surface. The sprinkler spacing was triangular, 18 by 15 m. The sprinklers and nozzles were manufactured by VYRSA (Briviesca, Burgos, Spain). The sprinkler model was “VYR 70”. The nozzle operating pressure was kept constant during the season at 300 kPa. In this sprinkler configuration, the resulting *CU* under calm conditions was high (above 94 %). The sprinkler discharge was volumetrically measured to be 0.48 L s^{-1}. The irrigation depth for each irrigation event was determined from this discharge, the irrigation time and the sprinkler spacing.

A corn crop (Zea mays L. cv. Dracma) was planted on May 17, 2000, at a density of 8 plants m^{-2}, with the rows being 0.75 m apart. Fertilisation consisted of 667 kg ha^{-1} of a 9-18-27 complex applied before sowing, and 234 kg N ha^{-1} as Ammonium Nitrate applied on June 1. Pests and weeds were controlled according to best management practices in the area.

Two experimental plots (hereafter designated as plot A and plot B) were selected in the field as shown in Figure III.1a. In each plot, twenty-five square parcels (1.5 m in side) were marked. Berms were built around them to prevent surface runoff. These parcels were the basic units for all the measurements performed during the experiment. Two catch cans were installed in the middle of each parcel and maintained at approximately the same height than the crop canopy (the height of the catch cans was increased from 0.36 m to 2.16 m throughout the season). Twenty-five access tubes for soil water content measurements by neutron probe (Model 3320, Troxler Electronic Laboratories, North Carolina) were installed to a depth of 1.5 m in each parcel of plot A. Details of the design of plot A are presented in Figure III.1b.

Crop water requirements and irrigation scheduling

Meteorological data were daily recorded using an automatic station (Campbell Scientific, Logan, Utah) located about 200 m of the experimental parcel. These data were used to compute the daily crop water requirements during the corn cycle. The daily corn evapotranspiration (*ETc, mm*) was estimated from daily values of reference evapotranspiration (*ETo, mm*) calculated using the FAO Penman-Monteith equation, and from tabulated crop coefficients (K_c) following the FAO approach (Allen et al., 1998). During all the experiment, two-minute averages of wind speed and direction were recorded in the abovementioned meteorological station. For each irrigation event the average wind speed ($W, m\ s^{-1}$) was determined, and a statistical analysis was performed on the evolution of the wind speed and direction.

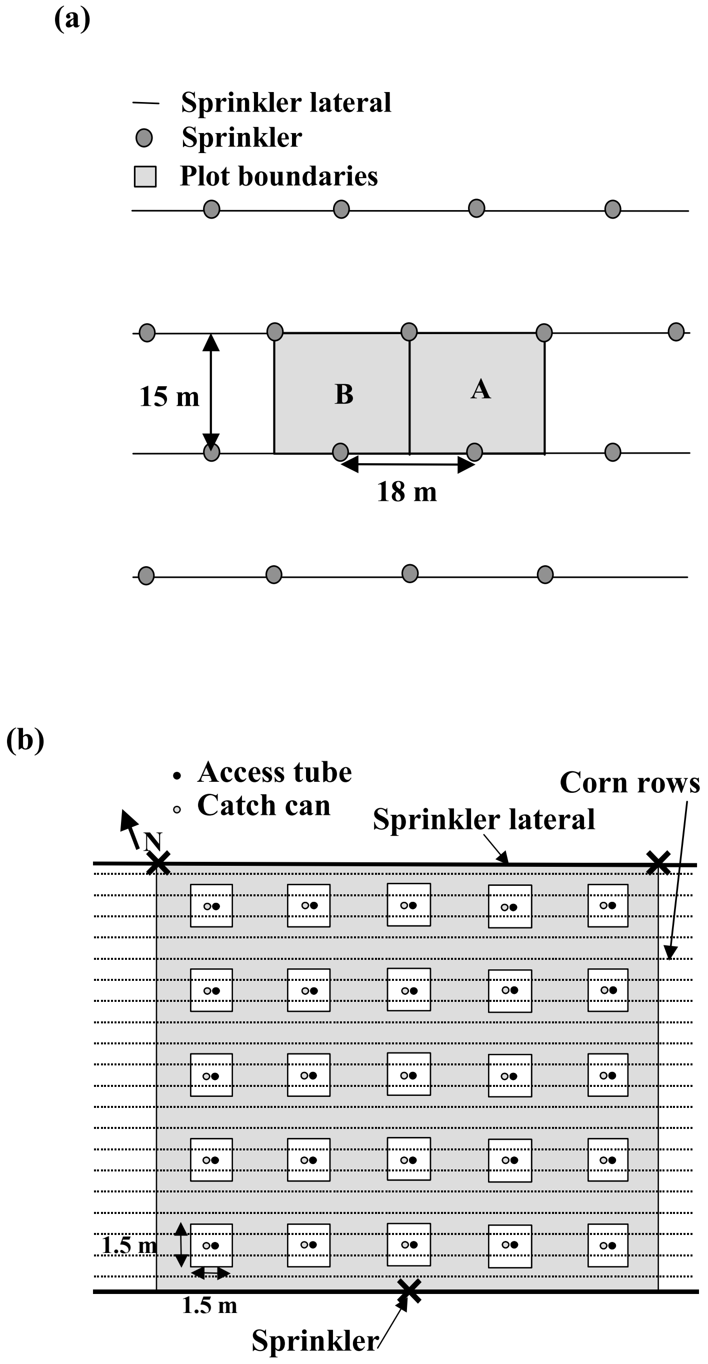

Figure III.1. *Design of the field experiment: (a) general experimental setup; and (b) detail of plot A.*

Figura III.1. *Diseño del experimento de campo: (a) diseño general del experimento; and (b) detalle del marco A.*

An initial irrigation event (irrigation # 0) was applied in June 1 with a dose of 25 mm. This irrigation event was not evaluated in detail, and therefore its results were only used for irrigation scheduling purposes. This irrigation was performed when water stress was observed in approximately 25 % of the plants. For the rest of the season, the irrigation schedule criterion was changed, and irrigations were performed when the soil water balance indicated that the level of allowable water depletion (50 % of the total available water) had been reached. Each irrigation event lasted for the time required to regain field capacity. The daily evolution of the average soil water content (SWC_i, *mm*) was determined at the time when the initial soil water content was gravimetrically measured. Daily soil water content was updated as:

$$\mathrm{SWC_i = SWC_{i-1} + P_i + IDc_i - ETc_i} \ , \qquad [1]$$

where SWC_{i-1} is the average soil water content on day *i-1* (mm); P_i is the precipitation for day i (mm); IDc_i is the catch can irrigation dose for day *i* (mm); and ETc_i is the crop evapotranspiration for day *i* (mm). Runoff was assumed to be negligible because the field was laser levelled to zero slope and each parcel was surrounded by earthen berms. Drainage below the rooting depth was equally neglected for scheduling purposes. According to this approach, a total of 23 additional irrigation events were applied during the whole corn cycle. Figure III.2 presents the cumulative *ETc* and water applied (catch can irrigation dose plus precipitation) during the growing season. At the beginning of the season a light overirrigation can be appreciated. Towards the end of the corn cycle, irrigation was slightly deficitary, in order to avoid an excess in soil water at harvest, following the local farmers' practice.

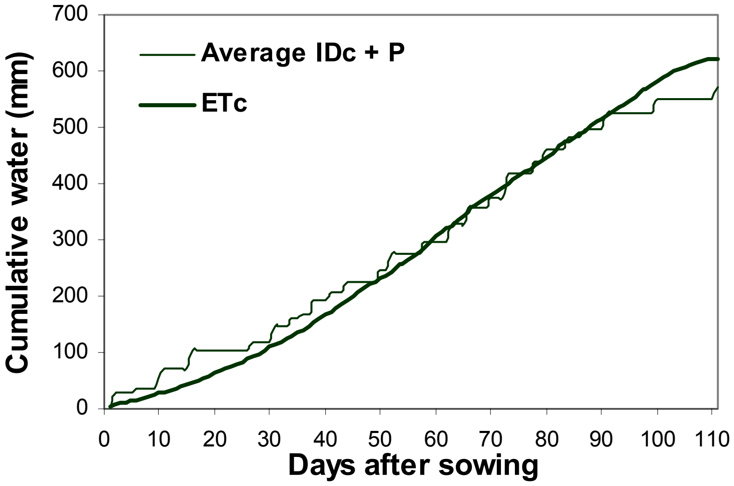

Figure III.2. *Time evolution of cumulative average catch can irrigation dose plus precipitation [IDc+P] and crop evapotranspiration [ETc], used for irrigation scheduling purposes.*

Figura III.2. *Evolución temporal de la dosis de riego acumulada media recogida en los pluviómetros más la precipitación (IDc+P) y de la evapotranspiración del cultivo [ETc], usados para la programación de riegos del ensayo.*

Measured soil Properties

Selected soil properties were analysed in each parcel of both plots, by 0.3 m layers and to a depth of 1.5 m when possible. The analysed properties included texture and gravimetric water content at field capacity (w_{FC}) and wilting point (w_{WP}). These gravimetric measurements were computed at the laboratory using pressure plates. Considering the soil texture, pressures of 0.02 and 1.5 MPa were considered representative of field capacity and wilting point, respectively. The average bulk density was determined as 1.45 Mg m^{-3} from the 18 samples collected for the calibration of the neutron probe and discussed in the next paragraph. Bulk density was used to determine the corresponding volumetric water contents (θ). Soil depth was measured during the soil sampling performed to determine soil properties. All these properties were combined to determine the total soil available water (*TAW, mm*) as defined by Walker and Skogerboe (1987).

The field calibration of the neutron probe was performed at 0.15 m intervals to a depth of 1 m. A total of 18 points were read and undisturbed soil samples were extracted to determine the volumetric water content. The regression analysis (neutron probe measurements *vs.* measured volumetric water content) yielded a determination coefficient (R^2) of 0.96. The neutron probe readings were performed only in plot A at an interval of 0.30 m and to a depth of 1.5 m. The readings were taken one day before and one day after four irrigation events distributed along the season.

In each experimental parcel of both plots, the gravimetric water content and the 1:5 soil extract electrical conductivity ($EC_{1:5}$) were measured at the same 0.30 m layers at sowing and harvest times. The electrical conductivity of the soil saturation extract (EC_e) was estimated from $EC_{1:5}$ using the relationship obtained by Isla (1996) at the same experimental field.

Irrigation evaluation

After each irrigation event the water collected in both catch cans of each parcel was averaged and recorded as the catch can irrigation dose (*IDc, mm*). The *IDc*'s corresponding to each irrigation event were used to compute the Christiansen uniformity coefficient *CU*, (Christiansen, 1942) and the Distribution Uniformity, *DU*, (Merriam and Keller, 1978). These parameters were computed separately for plots A and B for each irrigation event. Seasonal coefficients were also computed for each plot from the cumulative *IDc* applied to each parcel. The classification of *CU* values proposed by Keller and Bliesner (1991) was used in this work. The wind drift and evaporation losses (*WDEL, %*) produced during each irrigation event were computed from the irrigation dose discharged by the sprinkler system (*IDd*, obtained from the sprinkler discharge, the spacing and the duration of the irrigation event, and expressed in mm) and the average *IDc* ($\overline{\mathrm{IDc}}$):

$$WDEL = \frac{IDd - \overline{IDc}}{IDd} 100 \qquad [2]$$

A similar principle can be applied to each parcel in a given irrigation event. In this case, a deficit coefficient (C_D) can be computed to express the water deficit after each irrigation event in points receiving less water than *IDd*. The deficit coefficient (C_D) and the seasonal deficit coefficient (C_{DS}) were computed following the expressions:

$$C_D = \frac{IDd - IDc}{IDd} 100 \quad ; for \quad IDd > IDc \qquad [3]$$

$$C_{DS} = \frac{IDd_S - IDc_S}{IDd_S} 100 \quad ; for \quad IDd_S > IDc_S \qquad [4]$$

where the subscript "S" indicates seasonal, cumulative values.

In order to compare the irrigation depth collected in the twenty-five catch cans of both plots during each irrigation event, the Root Mean Square Error (*RMSE*) of the application rate was determined as:

$$RMSE = \frac{1}{25\,t} \sqrt{\sum_{i=1}^{25} \left(IDc_{iA} - IDc_{iB}\right)^2} \qquad [5]$$

Where *t* represents the duration of the irrigation event. The *RMSE* was used to quantify the differences in the water application pattern between two adjacent identical sprinkler spacings irrigated at the same time and under similar environmental conditions.

Corn Yield and seasonal irrigation water applied

At crop maturity, the aerial parts of corn plants from all parcels in plots A and B were hand harvested. The ears were separated from the rest of the plants and were oven dried at 60ºC to constant weight. The grain was separated from the corncob, its moisture was measured and the resulting weight was adjusted to represent a moisture content of 14 %. The analysed crop yield parameters included corn grain yield at moisture content of 14 % (*GY*, $kg\ ha^{-1}$) and total dry matter (*TDM*, $kg\ ha^{-1}$).

Data analysis

The statistical analysis of data and derived variables from the experiment was performed using the SAS statistical package (SAS, 1996). The procedures used were PROC REG and PROC CORR for regression and correlation analysis, respectively. The statistical significance levels considered in all the analyses were: "*ns*" to indicate non significant ($P > 0.05$); "*" to indicate $0.05 \geq P > 0.01$; "**" to indicate $0.01 \geq P > 0.001$; and "***" to indicate $0.001 \leq P$.

RESULTS AND DISCUSSION

Irrigation water distribution pattern analysis

Table III.1 presents the characteristics of the 23 evaluated irrigation events. In 56 % of them, the average wind speed was lower than the value of 2.1 m s^{-1} reported by Faci and Bercero (1991) as the threshold for an accused descent of the *CU* in the middle Ebro valley conditions. In 22 % of the irrigation events wind blew from all directions, and the average wind speed in these cases was lower than 2 m s^{-1}. Nearly 50 % of the frequent wind directions correspond to either Northwest winds (*cierzo,* in the local terminology) or Southeast winds (*bochorno*, in the local terminology). The highest average wind speeds correspond to the *cierzo* spells. This wind pattern is very common of the middle Ebro valley area (Faci and Bercero, 1991).

According to Ayers and Westcot (1989), the salinity of the water used for irrigation in this experiment (average EC_w of 1.78 dS m^{-1}) is above the threshold values for corn (1.1 dS m^{-1}). These authors report that the expected yield should be about 90 % of maximum. The *IDd* ranged from 12.8 mm to 44.8 mm between irrigation events, while the average *IDc* varied from 9.7 mm to 32.4 mm. The seasonal amount of irrigation water applied was 664 mm, with a crop evapotranspiration of 623 mm. The values of *WDEL* ranged from 6 % to 40 %, with an average of 20 %. Therefore, the seasonal wind drift and evaporation losses amounted to 133 mm.

Table III.1. *Characteristics of the 23 evaluated irrigation events (Average wind speed [W], dominant wind direction [WD], water electrical conductivity [EC_w], Irrigation dose discharged [IDd], Cath can irrigation depth [IDc], average value of Wind Drift and Evaporation Losses [WDEL], values of the Christiansen Coefficient of Uniformity calculated for Plot A [CU_A] and plot B [CU_B] and Root Mean Square Error [RMSE] between the volume of water collected in both A and B catch can sets).*

Tabla III.1. *Características de los 23 riegos evaluados, así como el valor medio de las pérdidas de evaporación y arrastre [WDEL], el coeficiente de uniformidad de Christiansen calculado para los marcos A [CU_A] y B [CU_B], así como la raíz cuadrada del error cuadrático medio [RMSE] entre los volúmenes de agua recogidos en los pluviómetros de los marcos A y B.*

# irrigatio	W (m s^{-1})	WD (°)	EC_w (dS m^{-1})	IDd (mm)	IDc (mm)	WDEL (%)	CU_A (%)	CU_B (%)	RMSE (mm h^{-1})
1	4.8	90-135	1.60	19.2	11.6	39.6	66.2	63.5	1.27
2*	3.2	225-270	1.13	44.8	32.4	27.7	75.4	74.3	0.64
3	1.4	225-270‡	1.73	38.4	31.3	18.5	93.7	94.2	0.40
4	2.7	180-225	-	12.8	10.8	15.6	82.8	80.2	0.92
5	1.1	135-180‡	1.75	32.0	26.7	16.6	94.5	94.1	0.55
6	2.0	90-135‡	1.71	19.2	14.8	22.7	89.3	85.9	0.62
7	2.6	135-180	1.89	12.8	9.7	23.8	82.9	79.8	0.52
8	4.2	315-360	1.81	32.0	23.0	28.1	73.1	77.0	0.75
9*	5.3	315-360	2.02	26.1	16.6	36.4	51.6	57.8	1.13
10	1.2	135-180	2.07	25.6	21.3	16.8	91.4	91.8	0.39
11	2.4	180-225	1.31	38.4	29.6	22.9	73.8	73.6	0.44
12	0.6	0-45†	1.71	25.1	20.0	-	92.9	92.7	0.39
13*	3.1	135-180	1.92	38.4	32.4	15.5	70.2	70.4	0.51
14	6.5	315-360	1.86	38.2	27.4	28.3	53.2	59.6	1.15
15	1.1	135-180	1.90	20.3	17.3	14.7	93.7	94.2	0.39
16	1.3	0-45	1.77	35.2	30.2	14.1	86.8	87.5	0.50
17	0.8	0-45†	1.82	26.7	22.9	14.0	89.2	87.1	0.63
18	1.2	45-90†	1.75	25.6	22.7	11.3	86.1	86.1	0.40
19	0.6	45-90†	1.71	19.2	18.0	6.0	89.8	88.2	0.51
20	0.7	0-45†	1.83	19.2	17.6	8.1	90.8	89.5	0.45
21*	1.0	0-45‡	1.76	32.0	28.3	11.4	88.7	87.4	0.63
22	6.2	270-315	-	32.0	21.9	31.4	51.3	57.3	0.79
23	1.8	225-270‡	2.29	25.6	21.7	15.2	81.2	80.4	0.41
Average	2.4	-	1.78	27.8	22.1	19.9	80.4	80.6	0.63

* Neutron probe measurements were performed before and after the irrigation event.

‡ A dominant wind direction was established, but wind blew from all directions during the irrigation event.

† Calm periods were recorded during the irrigation event.

– Unavailable data.

The spatial distribution of the water applied in plots A and B was different in each irrigation event. The extreme values of *CU* correspond neither to the highest average wind speed (irrigation 14, *W*= 6.5 m s^{-1}) nor to the lowest (irrigation 19, *W*= 0.6 m s^{-1}). This may be explained by the frequent changes of wind speed and direction during each particular irrigation event. The variability could also be observed in the difference between the volume of water collected in both A and B catch can sets during each of the 23 irrigations. The *RMSE* of the water collected in the catch can**s** attained maximum values when the wind speed was high and the wind direction range was narrow. Values of *RMSE* ranged from 0.39 mm h^{-1} to 1.27 mm h^{-1}, with an average of 0.63 mm h^{-1}. A regression analysis performed between the *CU* values computed in both plots indicated that the regression slope and intercept were not significantly different from 1 and 0, respectively (R^2 = 0.970^{***}).

In Figure III.3, two cases of water distribution during two consecutive irrigation events of the same duration are presented. The first case represents an irrigation event with low uniformity (irrigation 9, *CU*'s of 51.6 % and 57.8 % in plots A and B, respectively). The second case represents an irrigation event with high uniformity (irrigation 10, *CU*'s of 91.4 % and 91.8 % in plots A and B, respectively). It can be observed (particularly in irrigation 9) that the wind distortion of the water distribution pattern concentrates precipitation in particular areas of the experimental field. In irrigation 9 the *IDd* was 26.1 mm, but the values of *IDc* collected in the 25 parcels of both plots showed slightly different dispersions. The *IDc* in Plot A ranged from 4.5 to 38.5 mm, with an average of 17.6 mm and a *CV* of 58.1 %. In plot B the *IDc* ranged from 5.5 to 37.0 mm, with an average of 16.2 mm and a *CV* of 53.5 %. In this irrigation event, 76 % and 84 % of the catch cans in plots A and B, respectively, received an irrigation dose lower than *IDd*.

The *CU* of the irrigation events performed under wind speeds lower than the threshold value proposed by Faci and Bercero (1991) (52 % of the irrigation events) was larger than 84 %, except for irrigation 23, in which the *CU* was 81.2 % in plot A and 80.4 % in plot B. This could be due to the fact that during 37 % of the irrigation time the wind speed was slightly beyond the threshold value (with an average of 2.6 m s^{-1}), whereas the average wind speed was 1.8 m s^{-1}. The best fit between the wind speed and the *CU* of both plots was obtained with a third degree polynomial function (Figure III.4). This relationship explains 90 % of the variation of the *CU*. For wind speeds beyond 2 m s^{-1} the value of *CU* is clearly affected by the wind speed. This perception confirms the validity of the threshold value reported by Faci and Bercero (1991). Urrutia (2000), under similar experimental conditions, found an accused descent of the *CU* when the wind speed exceeded 3.5 m s^{-1}. This value almost doubles the threshold proposed by Faci and Bercero (1991).

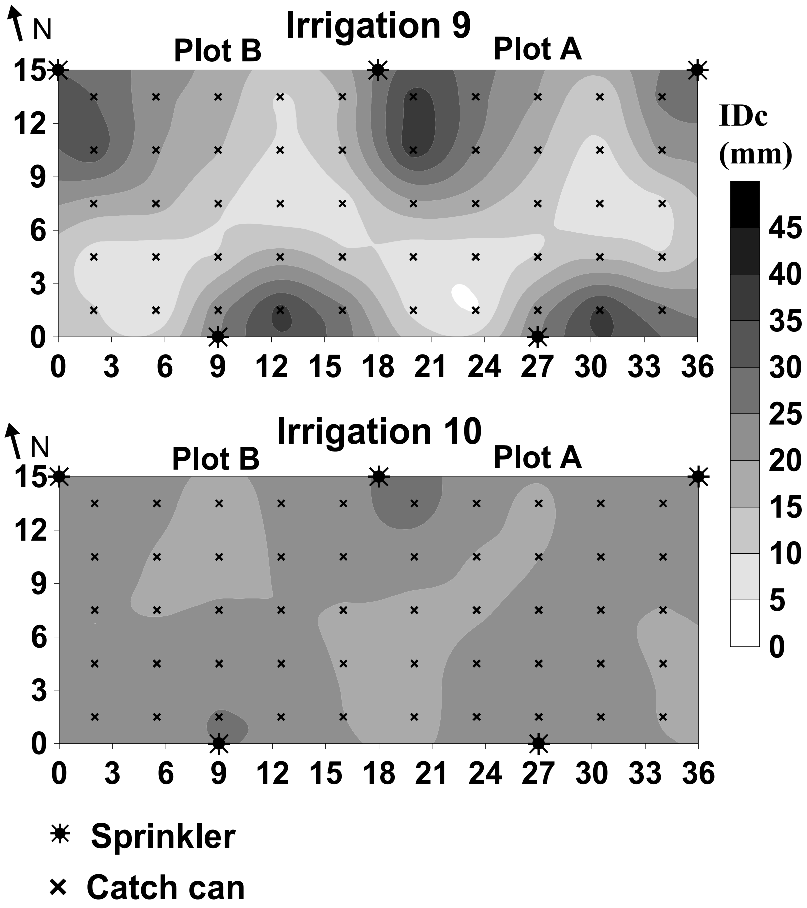

Figure III.3. *Water distribution pattern [IDc] of two consecutive irrigation events having the same duration. The recorded average wind speed was 5.3 m s^{-1} for irrigation 9 and 1.2 m s^{-1} for irrigation 10.*

Figura III.3. *Patrón de distribución de agua [IDc] de dos riegos consecutivos de la misma duración. El promedio del viento registrado fue de 5.3 m s^{-1} para el riego 9 y de 1.2 m s^{-1} para el riego 10.*

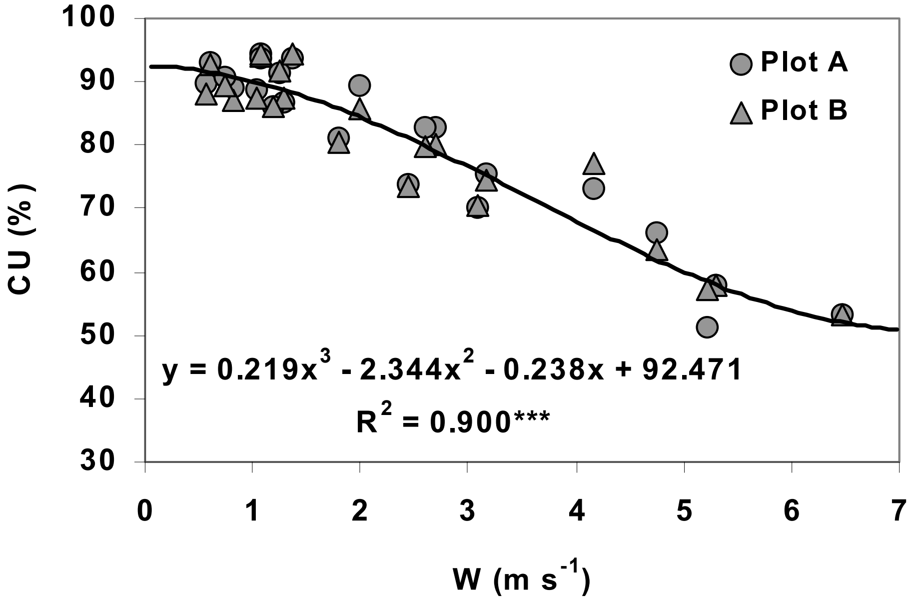

Figure III.4. *Christiansen Coefficient of Uniformity [CU] measured in plots A and B vs. wind speed [W].*

Figura III.4. *Coeficiente de uniformidad de Christiansen [CU] medido en los marcos A y B vs. velocidad del viento [W].*

The relationship between the wind speed and the *WDEL* of both plots showed that the data dispersion increases with the wind speed, particularly beyond 2 m s^{-1} (Figure III.5). This seems to be due to the variability of wind speed and direction during the irrigation time. In fact, heavy wind spells can induce drift losses that can not be explained by the average wind conditions. Both the lineal (R^2 = 0.810) and potential (R^2 = 0.792) regression models showed adequate fitting to the experimental data. Relevant differences between both models are observed for wind speeds below 0.5 m s^{-1}. In fact, for calm conditions the lineal and potential regression models estimate *WDEL* values of 7.5 % and 0.0 %, respectively. It will be difficult to assess which model is more adequate in the Ebro valley conditions, since it is not easy to find a calm period lasting for a few hours. The potential model does not seem adequate for low wind conditions, since there are reasons to believe that *WDEL* will always be greater than zero. The lineal model, however, may overestimate the *WDEL* under calm conditions.

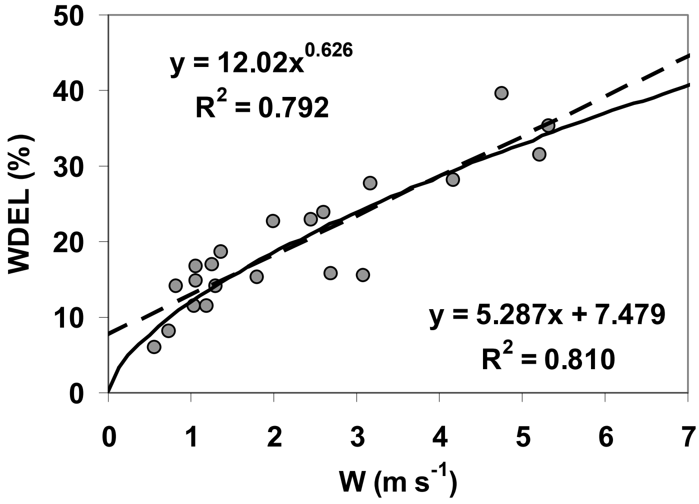

Figure III.5. *Average wind drift and evaporation losses [WDEL] for both plots vs. wind speed [W].*

Figura III.5. *Pérdidas medias de agua por evaporación y arrastre [WDEL] para ambos marcos vs. velocidad del viento [W].*

The average *CU* of all irrigation events can be classified as low (Table III.1), while seasonal irrigation had a high uniformity (*CU* of 88.0 % on the average of both plots). Indeed, the differences in wind speed and direction between irrigation events lead to a compensation process that results in the seasonal uniformity being higher than the average uniformity of the individual irrigation events. In this case the difference amounts to 7.5 %. This is frequent in sprinkler irrigation, due to the marked random character of the water distribution pattern (Dagan and Bresler, 1988). In an experiment performed with the same crop and in the same farm, but using surface irrigation, Zapata et al. (2000) found that the distribution uniformity (*DU*) was 5.2 % higher for the seasonal data than for the average of the irrigation events. In our work, if *DU* values were used (data not presented), the difference would be of 11 %. These results suggest that the wind induced randomness in sprinkler irrigation water application doubles the intensity of the compensation process found in surface irrigation.

Spatial variability of the measured soil properties

Soil depth in plot A reached 1.50 m in all parcels, while in plot B, soil depth varied from 1.03 m to 1.50 m. Plots A and B showed similar average values of the three textural classes in all soil layers (Table III.2). In addition, the upper layers (0 – 0.60 m) were characterized by a low spatial variability in the textural classes. The volumetric water contents at field capacity (θ_{FC}) and wilting point (θ_{WP}) showed low variability among soil layers and the highest average values were observed at the upper 0.30 m layer. As soil depth increases both θ_{WP} and θ_{FC} decrease. This could be attributed to the moderate increase in the sand fraction. The value of *TAW* is not clearly reduced at deeper layers, exception made of the two deepest layers in plot B, where the decrease in *TAW* is due to the reduced soil depth. In the top layers (0.0 – 0.60 m) the coefficient of variation of θ_{Wp} and θ_{FC} is small, and therefore the resulting spatial variability of the topsoil *TAW* is small. In deeper soil layers (0.60 – 1.50 m) the coefficients of variability approximately double those found at the upper layers. The variability of these soil properties in the deep layers should not have a relevant effect on the soil water regime, since the experimental *IDc* (22 mm per irrigation event on the average) is small in comparison with the top layers *TAW* (which averaged 101.9 mm, with a *CV* of 8.6 %).

This circumstance could reduce the dependence of sprinkler irrigated corn water status and yield on soil physics. Zapata et al. (2000) reported this dependence as being very relevant in surface irrigated corn.

The average EC_e was slightly higher in plot B at harvest than in plot A (Table III.2). -In the top layer (0 – 0.30 m) soil salinity decreased along the growing season, while in the 0.30 – 1.50 m layers there was a moderate increase in salinity. This increase was particularly relevant at the 0.60 – 0.90 m and 0.90 – 1.20 m layers of plot B. Considering all the soil profile, the increase in soil salinity from sowing to harvest time was 0.09 dSm^{-1} in plot A and 0.78 dSm^{-1} in plot B. The soil salinity found in our experimental site is above the published soil salinity tolerance threshold values for corn (1.7 dSm^{-1}, Ayers and Westcot, 1989). Under these soil salinity conditions the expected yield should be reduced to 50 – 75 % of the potential yield. However, several authors have reported that yield is unaffected by salt stress at moderate water stress levels, while in full irrigation schedules salt stress can cause significant yield reductions (Russo and Bakker, 1987; Shani and Dudley, 2001).

Relationship between irrigation water distribution and soil water content

The spatial distribution of soil water after each irrigation event was characterized by the Christiansen uniformity coefficient of soil water content (CUs_a) as proposed by Li (1998). Figure III.6a illustrates the relationship between the uniformity of irrigation water (CU) and the uniformity of soil water content within the soil perfil ($CUs_{a1.50}$) for irrigations 2, 9, 13 and 21. $CUs_{a1.50}$ values were very high (above 94 %) for all the considered irrigation events and there was no significant statistical relationship between both variables. The results obtained by Stern and Bresler (1983) and Li (1998) under similar experimental conditions showed that CUs_a exceeded 90 % even when the CU was below 70 %. In this research, however, $CUs_{a1.50}$ reached values between 94 and 95 % even for very low irrigation uniformities ($CU = 51$ %).

Only the upper soil layer (0 – 30 m) showed a significant increment in its water content following each irrigation event. Considering only the upper soil layer, soil water uniformity values ($CUs_{a0.3}$) were also higher than CU (Figure III.6b), increasing as the CU increased ($R^2 = 0.924^*$). Hart (1972), Li and Kawano (1996) and Li (1998) reported that sprinkler irrigation water was more uniformly distributed in the soil (CUs) than at the soil surface (CU) because of the redistribution of irrigation water in the soil. Under this hypothesis, the available soil water for the crop would be quite similar in the field and consequently the crop yield would show a lower variability due to the non-uniformity of the irrigation water.

Prior to each irrigation event, the upper soil water content tends to reach a uniform value controlled by crop water extraction and soil physical properties. In order to prove this hypothesis, Figure III.6c was prepared. A scatter plot presents the CU of the previous irrigation event (CU_{i-1}) *vs.* the soil coefficient of uniformity before the irrigation event at the upper layer ($CUs_{b0.30}$). The values of this last variable were systematically high (beyond 92 %), and showed no statistical relationship with CU_{i-1}.

Table III.2. *Textural class, volumetric water content at field capacity [θ_{FC}] and wilting point [θ_{WP}], total available water [TAW] and electrical conductivity at sowing [EC_e-s] and harvesting [EC_e-h] measured in each parcel of both plots, by 0.3 m layers and to a depth of 1.5 m when possible. Coefficients of variation are presented in parenthesis.*

Tabla III.2. *Clases texturales, contenido volumétrico de agua a capacidad de campo [θ_{FC}] y punto de marchitez [θ_{WP}], agua total disponible [TAW] y conductividad eléctrica saturada a la siembra [EC_e-s] y cosecha [EC_e-h] medidas en cada parcela de ambos marcos, en capas de 0,3 m de profundidad y hasta una profundidad total de 1,5 m allí dónde fue posible. Los coeficientes de variación se presentan en paréntesis.*

Soil layers (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} (%)	θ_{WP} (%)	TAW (mm)	EC_e-s (dS m^{-1})	EC_e-h (dS m^{-1})
Plot A								
0-0.3	52.9 (2.9)	34.2 (6.4)	12.8 (12.6)	26.4 (6.4)	9.6 (3.7)	50.3 (9.9)	5.1 (15.8)	4.6 (15.5)
0.3-0.6	56.4 (7.6)	31.5 (12.7)	12.0 (12.4)	24.8 (7.3)	8.6 (7.7)	48.4 (8.7)	4.7 (13.1)	4.9 (12.0)
0.6-0.9	56.0 (13.1)	32.7 (21.1)	11.2 (10.0)	24.9 (13.6)	8.0 (14.5)	50.8 (15.2)	4.3 (15.1)	4.8 (14.3)
0.9-1.2	56.2 (12.8)	34.0 (18.7)	9.6 (16.4)	24.6 (15.6)	7.0 (14.8)	52.7 (17.4)	3.9 (17.3)	4.2 (15.6)
1.2-1.5	59.9 (21.2)	30.2 (37.2)	9.4 (19.8)	24.0 (22.3)	6.6 (23.7)	52.2 (23.2)	4.0 (18.9)	4.1 (29.8)
Plot B								
0-0.3	49.0 (5.7)	36.8 (7.9)	14.0 (10.2)	27.4 (4.4)	9.5 (5.8)	53.5 (7.4)	5.6 (16.0)	5.1 (16.1)
0.3-0.6	52.3 (6.6)	36.1 (10.3)	11.6 (18.4)	25.2 (5.8)	8.0 (6.8)	51.4 (8.5)	5.0 (10.4)	5.7 (17.3)
0.6-0.9	56.8 (14.0)	32.9 (20.8)	10.3 (19.3)	23.6 (13.9)	6.2 (17.1)	52.0 (15.5)	4.3 (21.2)	5.8 (21.4)
0.9-1.2	55.4 (18.4)	34.8 (26.4)	9.8 (23.6)	23.9 (18.2)	5.9 (23.1)	47.7 (29.6)	3.9 (18.8)	5.5 (14.6)
1.2-1.5	44.4 (15.6)	36.9 (19.3)	9.8 (16.4)	24.8 (14.6)	6.6 (16.5)	32.5 (43.2)	4.4 (24.3)	5.0 (22.9)

The soil coefficient of uniformity for soil water recharge (θ_R), labelled $CUs_{R1.50}$, was always lower than the corresponding *CU* (Figure III.6d). This difference was particularly relevant for the lowest value of *CU*. The low values of *IDc* in some parcels may have resulted in a very shallow, centimetric water recharge, very prone to evaporation and difficult to measure accurately with the neutron probe. However, a significant linear regression was found between the uniformity of soil water recharge and *CU*, proving the link between catch can uniformity and soil water recharge uniformity. Therefore, it can be concluded that short-term soil water redistribution was not relevant in this experiment. These findings also announce the possibility of explaining the spatial variability of crop yield using catch can data.

A correlation analysis was performed between the catch can irrigation dose (*IDc*), the volumetric water content measured with neutron probe before and after the irrigation events (θ_b and θ_a, respectively) and the water recharge ($\theta_R = \theta_a - \theta_b$). This analysis was applied to irrigation events 2, 9, 13 and 21 (Table III.3). Correlation between θ_b and θ_a in each irrigation event was always high and strongly significant (ranging from 0.831^{***} to 0.990^{***}). The *IDc* applied in irrigations 2, 9 and 13 presented significant correlation coefficients with soil water recharge, varying from 0.527^{**} to 0.781^{***}. The best correlation was found for irrigation 9, characterized by the lowest value of *CU*. No significant correlation was found in irrigation 21. This seems to be due to the uniform water distribution (*CU* = 88.7 %, the highest among the four irrigation events with available soil water measurements). These findings suggest that the relationship between *IDc* and θ_R heavily depends on irrigation uniformity. The relationship between *IDc* and θ_a follows the same trend identified for *IDc* and θ_R. Finally, as expected, no statistical relationship could be established between *IDc* and θ_b in any of the four irrigation events.

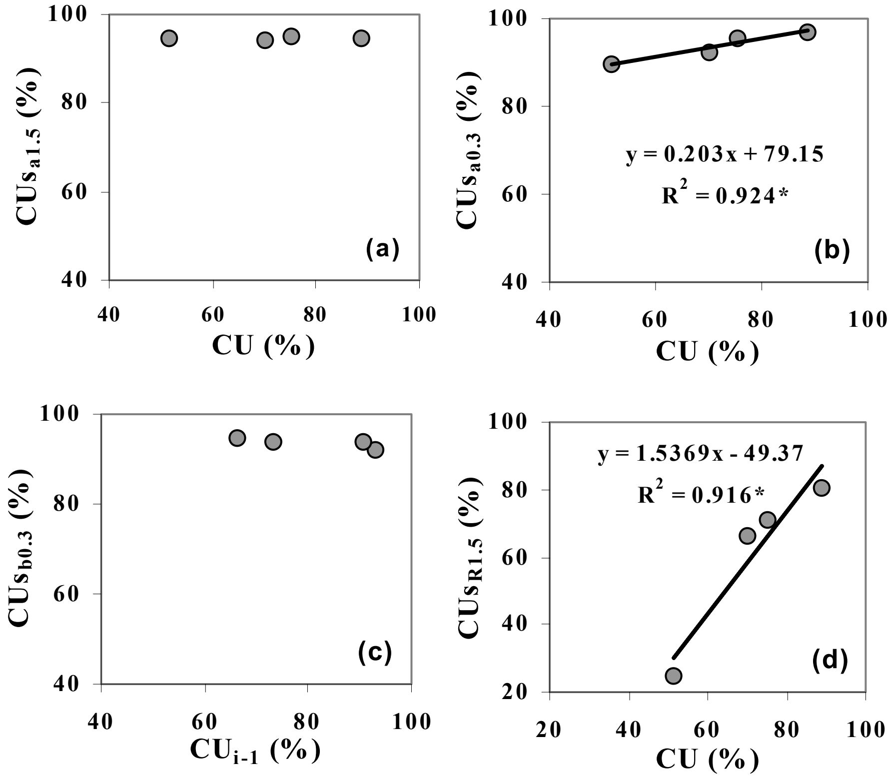

Figure III.6. *Soil water content uniformity [CUs] as a function of sprinkler water application uniformity [CU] for irrigation events 2, 9, 13 and 21; and considering CUs: (a) after the irrigation event in all soil profile [$CUs_{a1.5}$]; (b) after the irrigation event in the upper soil layer 0-0.30 m) [$CUs_{a0.3}$]; (c) before the irrigation event [$CUs_{b0.3}$] and vs. the previous irrigation event uniformity [CU_{i-1}]; and (d) calculated considering the soil water recharge [$CUs_{R1.5}$].*

Figura III.6. *Uniformidad del contenido de agua en el suelo [CUs] frente a la uniformidad de la aplicación de agua [CU] para los riego 2, 9, 13 y 21; y considerando CUs: (a) después del riego en todo el perfil del suelo [$CUs_{a1.5}$]; (b) después del riego en la capa de suelo superficial (0-0.30 m) [$CUs_{a0.3}$]; (c) antes del riego [$CUs_{b0.3}$] y vs. la uniformidad del riego previo [CU_{i-1}]; y (d) calculado considerando la recarga de agua del suelo [$CUs_{R1.5}$].*

An additional correlation analysis was performed to characterize the relationships between the considered irrigation events. The selected variables were θ_b, θ_a, θ_R and *IDc*. The soil water content before each irrigation ($\theta_{b\,i}$ *vs.* $\theta_{b\,j}$) and after each irrigation ($\theta_{a\,i}$ *vs.* $\theta_{a\,j}$) showed significant correlations in all cases. This can be explained by an additional fact: all the data sets for θ_b and θ_a showed significant correlations with

w_{fc} and w_{wp}, indicating that the water retention properties governed the local water content throughout the experiment. Concerning *IDc* and θ_R, significant correlations were only found for IDc_{13} *vs.* IDc_{21} (0.692***) and for $\theta_{R\,13}$ *vs.* $\theta_{R\,21}$ (0.475*). The remaining correlations for *IDc* and θ_R were non significant. It can be concluded that, in sprinkler irrigation, the spatial variability of the irrigation dose as determined with catch cans (*IDc*) or neutron probes (θ_R) strongly varies between irrigations. In a similar experiment in surface irrigation, Zapata et al. (2000) found strong correlations between the recharges corresponding to all pairs of irrigation events. The spatial variability of water application in sprinkler irrigation is therefore dictated by random variables such as wind speed and direction. From the presented correlation analyses, it can also be concluded that the catch can analysis is very representative of soil water recharge.

Table III.3. *Correlation matrix between catch can irrigation depth [IDc], volumetric water content measurement before [θ_b] and after [θ_a] the selected irrigation events and soil water recharge [θ_R].*

Tabla III.3. *Matriz de correlaciones entre la dosis recogida en los pluviómetros [IDc], el contenido volumétrico de agua medido antes [θ_b] y después [θ_a] de los riegos seleccionados, así como la recarga de agua debida al riego [θ_R].*

	Irrigation 2			**Irrigation 9**		
	θ_b (%)	**θ_a (%)**	**θ_R (mm)**	**θ_b (%)**	**θ_a (%)**	**θ_R (mm)**
IDc (mm)	0.306 ns	0.532 **	0.527 **	0.330 ns	0.568 **	0.781 ***
θ_b (%)		0.831 ***	0.146 ns		0.945 ***	-0.031 ns
θ_a (%)			0.670 ***			0.296 ns

	Irrigation 13			**Irrigation 21**		
	θ_b (%)	**θ_a (%)**	**θ_R (mm)**	**θ_b (%)**	**θ_a (%)**	**θ_R (mm)**
IDc (mm)	0.426 ns	0.632 ***	0.662 ***	0.368 ns	0.386 ns	0.158 ns
θ_b (%)		0.928 ***	0.068 ns		0.991 ***	0.008 ns
θ_a (%)			0.435 *			0.142 ns

Relationship between irrigation water distribution and deficit coefficient

The deficit Coefficient (C_D) was determined at the parcels receiving less water than *IDd* during each irrigation event (data not presented). In the following analyses, water deficit was only considered when C_D was higher than 10 %. This value represents a difference of 0.63 mm h^{-1} between the local values of *IDc* and *IDd*, and corresponds to the average value of Root Mean Square Error between the volumes of water collected in both plots (Table III.1). The magnitude of C_D is related to the water distribution pattern and to the wind drift and evaporation losses. Since these losses were relevant in our experimental conditions, deficit appeared in a large number of parcels.

In all 23 irrigation events, there were at least seven parcels in plot A and six in plot B where C_D exceeded 10 %. The irrigation water distribution pattern, conditioned by the wind speed and direction, induced continuous deficit (in all irrigation events) in a number of parcels (five in plot A and three in plot B). The location of these parcels within each plot is the same for three of them (located in the region between both sprinkler lines), representing 12 % of the plot area. This means that although water distribution was very uniform (with *CU*'s above 94 %), there was a continuous, localized water deficit. An additional amount of irrigation water should be applied in this case to maximize yield if economic and environmental factors allow.

This finding suggests that in sprinkler irrigation, characterizing the variability of irrigation water application using exclusively *CU* may not be an adequate choice. In fact, the value of *CU* does not provide an indication of the water deficit induced in the field. However, a relationship between *CU* and the average C_D can be derived. Figure III.7 presents the relationship between the *CU* and the average C_D of the plots with a C_D higher than 10 % corresponding to each irrigation event. Results showed a highly significant increase of the average C_D as *CU* decreased ($R^2 = 0.93^{***}$). Mantovani et al. (1995) and Li (1998), using an empirical model, reported the same trend (increased deficit with reduced *CU*), and applied it to irrigation decision making in a context of rising water prices. These authors considered a seasonal *CU* and a constant C_D for all the irrigation events applied during the crop cycle, while in this experiment, the average C_D obtained in each plot during each irrigation event and the corresponding *CU* were considered. The regression equation derived from our experiment can be used to estimate the average water deficit rate induced by any level of irrigation uniformity. This is important for sprinkler irrigation management in the middle Ebro river basin, since water is becoming increasingly scarce or expensive and the meteorological conditions (wind speed and direction) are frequently inadequate for sprinkler irrigation.

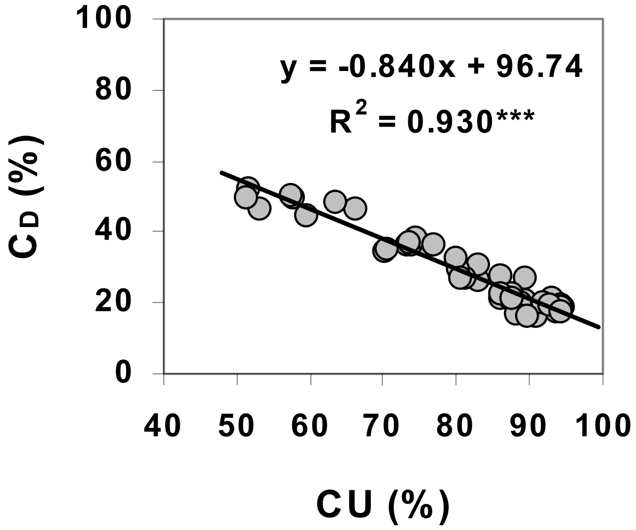

Figure III.7. *Average deficit Coefficient [C_D] vs. CU for each irrigation event and for each plot.*

Figura III.7. *Coeficiente de déficit (C_D) promedio vs. CU para cada marco y riego.*

Seasonal irrigation and yield response

In some parcels the seasonal irrigation dose exceeded the average *IDcs* and, however, the resulting yield (around 5,000 kg ha^{-1}) was well below the field average (7,129 kg ha^{-1}) (Figure III.8). In some of these parcels the low yield could be attributed to a low plant density (20 % lower than the average density of emerged plants). In the remaining parcels, the low yield was due to a very low infiltration rate, causing water stagnation leading to asphyxia in the root system. The following analysis was restricted to the rest of the parcels, i. e., the parcels marked in Figure III.8a were excluded.

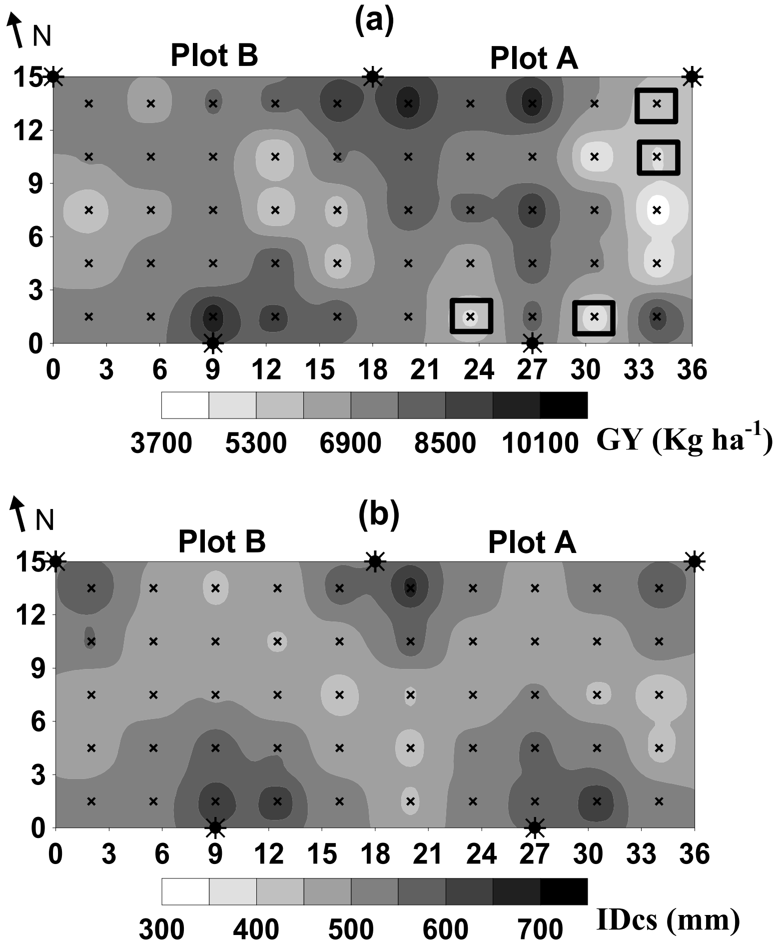

Figure III.8. *Contour maps of (a) grain yield (kg ha^{-1}); and (b) seasonal water (IDcs).*

Figura III.8. *Mapas de curves de nivel de (a) rendimiento en grano (kg ha^{-1}); y (b) agua estacional aplicada (IDcs).*

The values of the seasonal deficit coefficient (C_{DS}), seasonal catch can irrigation dose (*IDcs*), total dry matter (*TDM*) and corn grain yield (*GY*) were similar in plots A and B (Table III.4). Among these variables the seasonal C_{DS} showed the highest variability. The *GY* and *TDM* values obtained in each plot showed more variability than the IDcs, being slightly higher in plot A. The *CV* of *GY* was slightly higher than the *CV* of *TDM* in both plots. In a drip irrigation experiment, where wind does not affect water distribution, Or and Hanks (1992) found that the magnitude of yield variability was smaller than the magnitude of water application variability.

Table III.4. *General statistics for the seasonal deficit coefficient [C_{DS}], the seasonal irrigation catch can dose [IDcs], total dry matter [TDM] and grain yield [GY] measured or determined in plots A and B.*

Tabla III.4. *Estadísticos generales para el coeficiente de déficit estacional [C_{DS}], la dosis recogida en los pluviómetros estacional [IDcs], la materia seca total [TDM] y la producción en grano del cultivo [GY] medidos o determinados en los marcos A y B.*

Plot		**C_{DS} (%)**	**ID_{CS} (mm)**	**TDM (kg ha^{-1})**	**GY (kg ha^{-1})**
A	Minimum	11	391	7,660	3,769
	Maximum	39	680	17,560	10,102
	average	24	509	13,053	7,064
	CV	33	15	21	26
B	Minimum	12	399	10,024	4,831
	Maximum	37	654	17,490	10,013
	average	24	508	13,459	7,195
	CV	31	14	15	19
A and B	average	24	509	13,256	7,129
	CV	32	14	18	23

The minimum grain yield corresponds to the parcel receiving the minimum seasonal irrigation dose, while the highest yield was obtained in a parcel receiving slightly less than the average seasonal water application. The seasonal irrigation depths beyond 475–500 mm had no effect on yield (Figure III.9a). This threshold corresponds to 85–90 % of the calculated net irrigation requirement (*ETC – P*). If this analysis was performed using *IDd* instead of *IDc*, the conclusion would be that water applications of 107-112 % of the net irrigation requirement would lead to zero yield losses. Considering the total available water (Figure III.9b) (initial soil water content + irrigation + rainfall) a threshold around 600 mm can be observed. Below these threshold values for *IDcs* and total available water a decrease in grain yield was generally observed. These results are readily comparable to those reported by Cavero et al. (2001), based on the experiments performed by Zapata et al. (2000) in the same soil and crop, but using surface irrigation.

A correlation analysis was performed to characterize the effect on crop yield parameters (*TDM* and *GY*) of seasonal irrigation dose (*IDcs*), seasonal available water (initial soil water content + irrigation + rainfall), C_{DS}, EC_e at sowing and EC_e at harvest. No significant correlation was found between *GY* and CE_e neither at sowing nor at harvest. *GY* showed correlations with *IDcs* ($r = 0.502^{**}$) and seasonal available water ($r = 0.584^{***}$). C_{DS} was correlated with *GY* ($r = -0.513^{***}$), indicating that *GY* variability was partly dictated by the water deficit resulting from the non-uniformity of water distribution during the crop season.

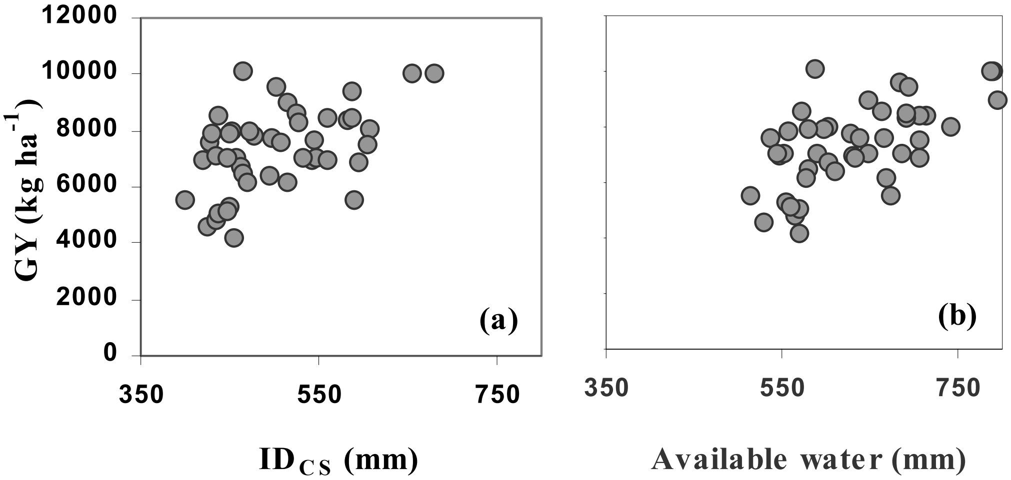

Figure III.9. *Relationship between grain yield [GY] and (a) ID_{CS}; and (b) crop available water (initial available water + irrigation + rainfall).*

Figura III.9. *Relación entre rendimiento en grano [GY] y (a) agua estacional aplicada [ID_{CS}]; y (b) agua disponible para el cultivo (agua inicial disponible + riego + lluvia).*

Concerning the correlation between *GY* and *IDcs*, the value obtained in this work is similar (though somewhat lower) than those reported in previous works performed in sprinkler irrigation systems (Stern and Bresler, 1983 ; Dagan and Bresler, 1988). In surface irrigation, and following the standard techniques of water application estimation (Merriam and Keller, 1978), Zapata et al. (2000) found a correlation of 0.45, slightly lower than the available references for sprinkler irrigation.

Yield response to the variability of water distribution in time and space

A correlation analysis was performed between crop yield parameters and the *IDc* corresponding to the 23 irrigation events. Only seven of them were significantly correlated with *TDM* and corn grain yield (Table III.5). These seven irrigation events were applied during the flowering and grain filling stages and had low *CU*'s (66.5 % on the average) (Table III.1). During that period, the remaining irrigation events, for wich *IDcs* were not correlated with *GY* and *TDM*, showed *CU* values above 86%. Non-uniform irrigation events applied before the flowering stage did not show a significant correlation with crop yield. The most significant correlations were found for irrigation events 8, 9 14 and 22, which had the highest C_D, ranging from 36 % to 52 %. These results illustrate the relevance of irrigation non-uniformity beyond the flowering stage in corn grain yield variability under sprinkler irrigation when the irrigation water depth applied is equal to the crop water requirements.

Table III.5. *Results of the correlation analysis between yield parameters [GY and TDM] and catch can irrigation dose [IDc] for each irrigation event. Only significant correlations are presented.*

Tabla III.5. *Resultados de un análisis de correlación entre parámetros de rendimiento [GY and TDM] y la dosis de agua recogida en los pluviómetros [IDc] en cada riego. Sólo se presentan las correlaciones significativas*

	IDc_8 (mm)	**IDc_9 (mm)**	**IDc_{11} (mm)**	**IDc_{13} (mm)**	**IDc_{14} (mm)**	**IDc_{22} (mm)**	**IDc_{23} (mm)**
TDM ($kg\ ha^{-1}$)	0.476 **	0.493 **	0.353 *	0.339 *	0.466 **	0.425 **	0.335 *
GY ($kg\ ha^{-1}$)	0.441 **	0.468 **	0.373 *	0.362 *	0.454 **	0.416 **	0.338 *

SUMMARY AND CONCLUSIONS

A field experiment was performed to study the effect of the space and time variability of water application on solid set sprinkler irrigated corn yield. The experimental design guaranteed high irrigation uniformity under low wind speed conditions. Irrigation was scheduled to fulfill corn water requirements during all growth stages assuming no wind effects, and applying light irrigations. Irrigation events were applied during variable meteorological conditions (wind speed and direction) inducing different spatial patterns of water distribution in each irrigation event. The following remarks and conclusions are supported by this study:

The *CU* values of 48 % of the irrigation events were lower than 84 % in both plots. The extreme values of *CU* corresponded neither to the highest average wind speed nor to the lowest. A large percentage (90 %) of the variability in *CU* was explained by the wind speed alone. This environmental factor also explained the 80 % of the wind drift and evaporation losses. The differences in wind speed and direction among irrigation events lead to a compensation process that results in the seasonal *CU* being higher than the average *CU* of the individual irrigation events (88.0 % *vs.* 80.5 %). The marked wind-induced random character of individual irrigation *CU* values induces doubts as to the representativity of the seasonal *CU*. In this case, the seasonal *CU* would fall in the category of uniform irrigation, while about half of the irrigation events were of questionable uniformity.

In this experiment, the dependence of sprinkler irrigated corn water status and yield on the analyzed soil properties was low. No evidence was found proving that the soil diminishes the heterogeneity induced by the irrigation water distribution. In fact, the uniformity of soil water recharge was lower than the irrigation water distribution uniformity, and the relationship between both variables was statistically significant ($R^2 = 0.916^*$). It was also found that the relationship between *IDc* and water recharge heavily depends on irrigation uniformity.

The magnitude of C_D is related to the water distribution pattern and to the wind drift and evaporation losses. Since these losses were very relevant in our experimental conditions (20 % on the average), water deficit appeared in a large number of parcels. Even in very uniform irrigation events, a number of parcels showed values of C_D over 10 % (in fact, 16 % of the parcels suffered continuous localized water deficit). As a conclusion, in sprinkler irrigation systems, characterizing the variability of irrigation water application using exclusively *CU* may not be an adequate choice. The average C_D

was significantly related with *CU*. This relationship can be used to determine the minimum *CU* required to ensure that all parts of the field receive an adequate amount of water.

GY presented more variability than *TDM* in both plots, and both *GY* and *TDM* showed more variability than *IDcs*. The variability of *GY* was due to the spatial and temporal variability of *IDc*, which limited the amount of crop available water and induced a variable crop water stress in time and space. Indeed, C_{DS} variability was higher than *GY* variability, and showed better correlation with *GY* than ID_{CS}. Non-uniform irrigations performed at or after the flowering stage resulted in significant correlations between *IDc* and *GY*. Therefore, farmers should be particularly careful at these crop growth stages in selecting the adequate wind conditions for irrigation. Events performed with wind speeds beyond the 2.1 m s^{-1} threshold will result in uneven water applications leading to either additional irrigation water application or water stress associated to relevant yield losses.

RESUMEN Y CONCLUSIONES

Se desarrolló un experimento de campo para estudiar el efecto de la variabilidad espacio-temporal de la aplicación de agua en dos marcos de un cultivo de maíz regado con una cobertura total de aspersión. El diseño experimental garantizó una elevada uniformidad de riego en condiciones de bajo viento. El riego se programó para satisfacer las necesidades de agua del cultivo durante su crecimiento, sin considerar los efectos del viento, y aplicando riegos ligeros. Los riegos se aplicaron en condiciones meteorológicas variables (velocidad y dirección del viento), lo que indujo diferentes patrones de reparto de agua en cada riego. Las siguientes conclusiones se pueden extraer de este estudio:

Los valores de *CU* del 48 % de los riegos fueron inferiores al 84 % en ambos marcos. Los valores extremos del *CU* no correspondieron ni al viento más alto ni al más bajo. Un gran porcentaje (90 %) de la variabilidad del *CU* fue estadísticamente explicado por la velocidad del viento. Este factor ambiental también explicó el 80 % de las pérdidas de agua por evaporación y arrastre. Las diferencias en la velocidad y dirección del viento entre riegos dieron lugar a un proceso de compensación que resultó en que el *CU* estacional fuera mayor que el promedio del *CU* de todos los riegos (88,0 % frente a 80,5 %). El marcado carácter aleatorio, inducido por el viento, de los valores de *CU* de los riegos individuales arroja dudas acerca de la representatividad del *CU* estacional. En este caso, el *CU* estacional podría clasificarse como de riego uniforme, mientras que la mitad de los riegos tuvieron una uniformidad cuestionable.

En este experimento, la dependencia del estado hídrico y el rendimiento del maíz regado por aspersión de las propiedades del suelo analizadas fue baja. No se encontró ninguna evidencia que probara que el suelo disminuye la heterogeneidad inducida por la distribución del agua de riego. De hecho, la uniformidad de la recarga del agua del suelo fue menor que la uniformidad de distribución del riego, y la relación entre ambas variables fue estadísticamente significativa (R^2 = 0,916*). También se encontró que la relación entre la dosis de riego y la recarga de agua de éste depende en gran medida de la uniformidad del riego.

La magnitud del coeficiente de déficit estuvo relacionada con el patrón de distribución de agua y con las pérdidas de agua por evaporación y arrastre. Puesto que estas pérdidas fueron muy relevantes en las condiciones experimentales (un 20 % del agua aplicada en promedio), hubo déficit en un gran número de parcelas. Incluso en riegos muy uniformes, un número de parcelas mostró valores del coeficiente de déficit superiores al 10 % (de hecho, un 16 % de las parcelas sufrió un déficit localizado continuo). Como conclusión, en sistemas de riego por aspersión, la caracterización de la variabilidad de la aplicación del agua de riego mediante el *CU* exclusivamente puede no ser una buena idea. El valor medio del coeficiente de déficit pudo ser signifiativamente relacionado con el *CU*. Esta relación se puede usar para determinar el mínimo *CU* necesario para asegurarse de que todas las partes del campo reciben una cantidad de agua adecuada.

El rendimiento del maíz mostró más variabilidad que la materia seca total en ambos marcos de aspersión, y ambas variables tuvieron más variabilidad que el agua aplicada estacional. La variabilidad del rendimiento se debió a la variabilidad espacial y temporal de la dosis de riego, que limitó la cantidad de agua disponible para el cultivo e indujo un estrés hídrico variable en el espacio y el tiempo. De hecho, la variabilidad del coeficiente de déficit estacional fue mayor que la del rendimiento, y el coeficiente de déficit estacional mostró mejor correlación con el rendimiento que la dosis de riego. Los riegos de baja uniformidad realizados durante la fase de floración o después se caracterizaron por una correlación significativa ente la dosis de riego y el rendimiento final. Por lo tanto, los agricultores deberían ser particularmente cuidadosos durante estas fases del cultivo a la hora de seleccionar condiciones ambientales adecuadas para el riego. Los riegos que se realicen con velocidades de viento superiores al umbral de 2.1 m s^{-1} darán lugar a distribuciones de agua poco uniformes que o bien necesitarán aplicaciones adicionales de agua de riego o darán lugar a un estrés hídrico que afectará negativamente a la producción.

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NOTATION

The following symbols are used in this chapter:

θ = volumetric soil water content (%);
θ_a = volumetric soil water recharge after irrigation (%);
θ_b = volumetric soil water recharge before irrigation (%);
θ_R = volumetric soil water recharge (%);
θ_{FC} = gravimetric water content at field capacity (mm);
θ_{WP} = gravimetric water content at wilting point (mm).
C_D = deficit coefficient (%);
C_{DS} = seasonal deficit coefficient (%);
CU = Christiansen Coefficient of Uniformity (%);
CUs = Christiansen uniformity coefficient of soil water content (%);
CUs_a = Christiansen uniformity coefficient of soil water content after irrigation (%);
$CUs_{a1.50}$ = Christiansen uniformity coefficient of soil water content after irrigation within the soil perfil (%);
$CUs_{a0.3}$ = Christiansen uniformity coefficient of soil water content after irrigation considering only the upper soil layer (%);
$CUs_{b0.30}$ = soil coefficient of uniformity before the irrigation event at the upper layer (%);
$CUs_{R1.50}$ = soil coefficient of uniformity for soil water recharge (%);
CU_{i-1} = Christiansen uniformity coefficient of the previous irrigation event (%);
CV = coefficient of variation (%);
DU = distribution uniformity (%);
$EC_{1:5}$ = electrical conductivity of the 1:5 soil extract (dS m^{-1});
EC_e = electrical conductivity of the soil saturation extract (dS m^{-1});
EC_w = electrical conductivity of the irrigation water (dS m^{-1});
ETc = crop evapotranspiration (mm);
ETc_i = crop evapotranspiration for day i (mm);
ET_0 = reference evapotranspiration (mm);
IDc = catch can irrigation dose (mm);
IDc_i = catch can irrigation dose for day i (mm);
$IDcs$ = seasonal catch can irrigation dose (mm);
IDd = sprinkler discharge dose (mm);
GY = grain yield (kg ha^{-1});
K_c = crop coefficient;
P_i = precipitation for day I (mm);
R^2 = determination coefficient;
$RMSE$ = Root Mean Square Error;
SWC_i = average soil water content on day i (mm);
SWC_{i-1} = average soil water content on day i-1 (mm);
T = duration of the irrigation event (s);
TAW = total soil available water (mm);
TDM = total dry matter (kg ha^{-1});
W = average wind speed (m s^{-1});
$WDEL$ = wind drift and evaporation losses (%);

LIST OF PICTURS


III.1


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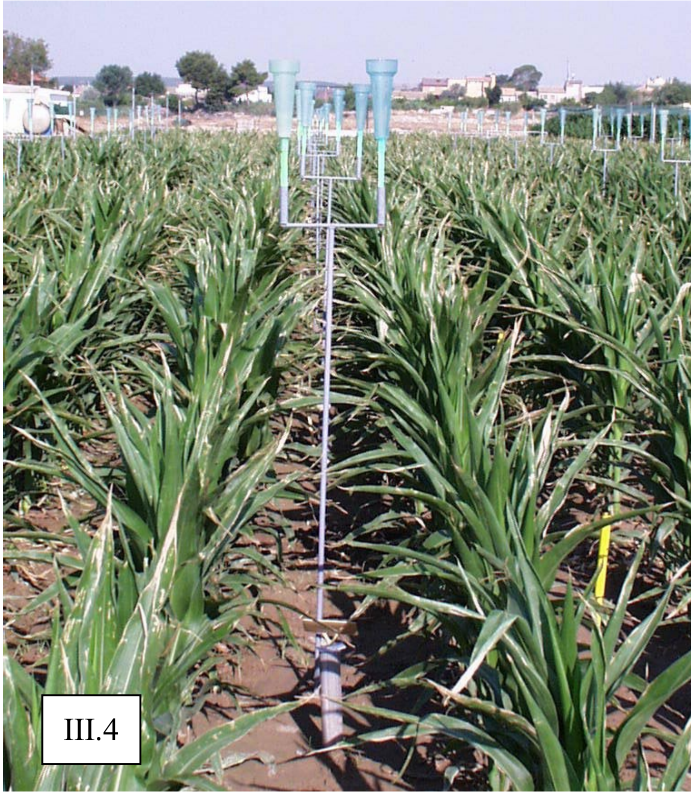
III.3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III.5

CHAPTER IV

A COUPLED CROP AND SOLID SET SPRINKLER SIMULATION MODEL: I. MODEL DEVELOPMENT

RESUMEN

En las últimas décadas se han introducido desarrollos relevantes en los modelos de cultivos y del riego por aspersión en cobertura total. En este trabajo se presenta la combinación del un modelo de cultivos (Ador-Crop) y de un modelo de riego por aspersión en cobertura total (Ador-Sprinkler). El modelo de cultivos incorpora muchas de las características del modelo CropWat. Sin embargo, se han introducido mejoras sustanciales respecto del modelo original, como el uso de tiempo térmico para el crecimiento de los cultivos y la introducción de datos diarios de evapotranspiración de referencia. El modelo de simulación del riego por aspersión en cobertura total aplica la teoría balística para determinar la distribución de agua que resulta de aspersores sujetos a un vector de viento. El modelo propuesto usa una ecuación de distribución de tamaño de gotas cuyos parámetros dependen del modelo de aspersor, del diámetro de las boquillas, de las condiciones meteorológicas y de la presión de trabajo. El modelo se calibró con experimentos de campo en dos marcos de aspersión adyacentes de una cobertura equipada con aspersores provistos de boquillas de 4,4 y 2,4 mm de diámetro, dispuestos triangularmente con un espaciamiento de 18 x 15 m. Los parámetros de distribución de los diámetros de gota identificados a partir de los experimentos de campo fueron D_{50} =1,30 mm, y n = 2,50. Se describió una relación funcional entre los parámetros correctores del coeficiente aerodinámico (K_1 y K_2) y la velocidad del viento. Para vientos inferiores a 1,1 m s^{-1} la corrección del coeficiente aerodinámico no fue necesaria. Una vez que se completó la fase de calibración, el modelo Ador-Sprinkler predijo adecuadamente la distribución del agua de riego durante todo el ciclo del cultivo. El valor medio del estadístico *RMSE* entre la aplicación del agua medida y simulada (0,95 mm h^{-1}) fue comparable al *RMSE* medio entre la aplicación de agua en los dos marcos experimentales adyacentes (0,63 mm h^{-1}).

Por lo tanto, una buena parte del error en la simulación pudo ser atribuido a errores experimentales. El modelo de cultivos se validó a través de una comparación con CropWat. Ambos modelos predijeron una reducción del rendimiento similar (R^2 = 0,988***). En cuanto a la validación del modelo AdorSim, la representación de los valores medidos y simulados de agua estacional disponible para el cultivo frente a la reducción de rendimiento mostró rasgos similares. El modelo combinado pudo explicar el 25 %** de la variabilidad de la reducción de rendimiento medida. La mayor parte de la variabilidad no explicada por el modelo resultó ser debida al efecto sobre el rendimiento de factores no relacionados con el agua. En el siguiente capítulo el modelo combinado se aplicará a la optimización del diseño de la parcela experimental y a la investigación de opciones avanzadas de gestión del riego en el valle medio del Ebro.

ABSTRACT

In the last decades relevant developments have been introduced in crop and solid-set sprinkler irrigation models. In this paper, the development of a coupled crop model (Ador-Crop) and solid set sprinkler irrigation model (Ador-Sprinkler) is presented. The crop model incorporates many of the features developed in the well-known CropWat model. Relevant improvements include the use of thermal time and the input of daily ET_0. The solid set sprinkler model applies ballistic theory to determine water distribution resulting from sprinklers subjected to a wind vector. The proposed model uses a drop size distribution equation whose parameters depend on the sprinkler type, nozzle diameters, meteorological conditions and operating pressure. The model was calibrated with field experiments performed in two adjacent plots on a corn crop irrigated with sprinklers equipped with 4.4 and 2.4 mm nozzles in a triangular spacing of 18 x 15 m. The drop size distribution parameters identified from field experiments and model runs were D_{50} = 1.30 mm and n = 2.50. A relationship was found between the corrector parameters of the aerodynamic drag coefficient (K_1 and K_2) and the wind speed. For wind speeds below 1.1 m s^{-1}, correction was not required. Once the calibration phase was completed, Ador-Sprinkler adequately predicted irrigation water distribution during the whole corn development cycle. The average *RMSE* between measured and simulated water application (0.95 mm h^{-1}) was comparable to the average *RMSE* between the measured water distributions in two adjacent plots (0.63 mm h^{-1}). Therefore, a relevant part of the simulation error could be attributed to experimental errors. The crop model was validated through a comparison with CropWat. Both models produced similar yield reduction results (R^2 = 0.988***). Regarding the AdorSim validation, the plot of soil available water *vs.* measured and simulated yield reduction resulted in similar features. The coupled model explained 25 %** of the variability in measured the measured yield reduction. Most of the unexplained variability is due to the effect non water-related factors affecting crop yield. In a companion paper, the coupled model will be used to investigate optimum water management options in the middle Ebro valley in NE of Spain.

INTRODUCTION

High uniformity of irrigation water distribution and appropriate irrigation scheduling practices are required to optimize irrigation efficiency, yield and economic benefits. These practices may also lead to significant water conservation, reduced environmental impact and improved sustainability of irrigated agriculture (Smith et al., 1996). In sprinkler irrigation, the water distribution pattern is strongly affected by wind speed. Consequently, some areas of the field may not receive an adequate amount of irrigation water (Seginer et al., 1991; Faci and Bercero, 1991; Tarjuelo et al., 1994; Kincaid et al., 1996). Wind effects can be considered when designing a sprinkler irrigation system if the area is subjected to nearly constant wind speed and direction (Vories et al., 1987). While in some areas the wind direction shows a clear pattern, wind speed and direction are often subjected to a large variability within a given day and among days. This circumstance poses a serious limitation to the adequate design of sprinkler irrigation systems and makes water management a difficult task.

Field evaluations have been used to diagnose existing sprinkler irrigation systems and to determine optimum operating conditions (pressure, nozzle size and sprinkler spacing) (Tarjuelo et al., 1992). However, field evaluations may be unpractical when it comes to test a wide variety of irrigation variables under windy conditions because of 1) the cost and work involved; and 2) the difficulty to reproduce specific environmental conditions. Properly calibrated simulation models of sprinkler irrigation have emerged as useful tools to predict irrigation performance parameters such as the Christiansen Coefficient of Uniformity (*CU*) (Christiansen, 1942) for any combination of operating and meteorological conditions (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991b; Tarjuelo et al., 1994; Carrión et al., 2001). However, *CU* does not provide information on the wind-induced areas of water deficit and surplus (See chapter III). This may be very important when sprinkler irrigation is analysed from the agronomic, economic and environmental points of view.

Several authors have proven that the spatial variability of crop available water is responsible for most of the spatial variability in crop yield (Stern and Blesler, 1983; Warrick and Gardner, 1993; Or and Hanks, 1992). In irrigated fields, soil water availability at a given point depends on the spatial variability of soil water properties and on the uniformity of water application. The relationship between irrigation uniformity and the variability of crop yield has been analyzed using crop models and considering a constant irrigation water distribution pattern during all crop growth stages (Orgaz et al., 1992; Mantovani et al., 1995; de Juan et al., 1996; Li, 1998). However, irrigation uniformity varies with the meteorological conditions (particularly with the wind speed). This aspect is particularly important in order to adopt appropriate water management rules, although its modeling is complex.

The objective of this research is to develop a model capable to predict the effect of the variability in time and in space of sprinkler irrigation water on crop yield. The model makes use of two related disciplines: irrigation engineering and agronomy. The sprinkler irrigation module simulates irrigation water application in a square grid within a given sprinkler spacing. The crop module simulates the yield reduction at the same grid locations taking into account the simulated application depth and the soil proprieties at each point of the field. The model theoretical basis, description, calibration and validation are presented in this paper. In chapter V, the model is applied to identify adequate sprinkler irrigation design and management rules for the central Ebro Basin (NE Spain), with particular reference to wind effects.

WATER STRESS IN CROP MODELS

Crop response to water supply may be summarized in a function relating yield to the seasonal amount of water made available to the crop. Solomon (1983) reviewed the literature on water-yield functions and presented typical functions for many agricultural crops. In the last decade, numerous models have been developed to simulate crop growth and water balance. These models help to identify factors controlling crop yield and evapotranspiration. Among the models that have been developed for this task, a distinction can be made between crop growth simulation models, simulating the main processes of crop growth (leaf rea growth, biomass production and partition (Jones and Kiniry, 1986; Stockle et al., 1994; Williams et al., 1984; Brisson and Mary, 1996), and those models that do not explicitly simulate crop growth (Smith, 1993). The first type of models takes account of dynamic processes and therefore requires more extensive input parameters than the second type.

Since it is difficult to assess soil hydraulic properties, models using simplified approaches to soil water flow and crop growth are often used. In fact, Cabelguenne (1996) found that at least 140 crop models had been developed based on the water production functions proposed by Stewart et al. (1977) and applied by Doorenbos and Kassam (1979). Following this approach, water stress affects crop yield through crop response factors:

$$1-\frac{Y_a}{Y_{max}}=K_y\left(1-\frac{ET_a}{ET_{max}}\right) \qquad [1]$$

Where Y_a is the actual yield, Y_{max} is the maximum yield, ET_a is the seasonal crop evapotranspiration, ET_{max} is the maximum seasonal crop evapotranspiration and K_y is a coefficient representing crop yield sensitivity to water deficit. K_y values are available in the for numerous crops (Doorenbos and Kassam, 1979).

NUMERICAL MODELS FOR SOLID SET SPRINKLER IRRIGATION

A number of sprinkler irrigation simulation models considering wind distortion have been developed in the last decades (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991; Tarjuelo et al., 1994; Carrión et al., 2001). In these models, a sprinkler is considered as a device emitting drops of different diameters with a given initial velocity vector. A ballistic approach is used to model the drop trajectory until reaching the ground surface. The ballistic theory applied to water drops in the air considers that the movement of a drop is influenced by 1) its initial velocity vector; 2) gravity, acting in the vertical direction; 3) the wind vector; and 4) the resistance force (*Fr*), applied in a direction opposite to the relative movement of the drop in the air (Vories et al., 1987; Seginer et al. 1991). According to Seginer et al. (1991), the *Fr* for an isolated drop can be determined as:

$$Fr = \frac{1}{8}\rho_a C\pi D^2 V^2 = mC_2 V^2 \qquad [2]$$

Where: *m* is the mass of the water drop, *V* is the velocity of the drop in the air, ρ_a is the air density, *D* is the drop diameter, and *C* is the drag coefficient. Under no wind conditions, the drop velocity with respect to the ground (*U*) is equal to *V,* while under wind condition *U* is equal to the sum of vector *V* and the wind velocity vector (*W*), which is supposed to act in the horizontal plane.

A summation of forces acting on the drop leads to a differential equation describing the path of individual drops of water emitted by a sprinkler nozzle. The three directional components of the movement of each drop can be expressed as follows (Fukui et al., 1980):

$$A_x = \frac{d^2x}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_x}\frac{C}{D}V\left(\frac{dx}{dt} - W_x\right) = -C_2 V\left(U_x - W_x\right) \qquad [3]$$

$$A_y = \frac{d^2y}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}V\left(\frac{dy}{dt} - W_Y\right) = -C_2 V\left(U_Y - W_Y\right) \qquad [4]$$

$$A_z = \frac{d^2z}{dt^2} = -\frac{3}{4}\frac{\rho_a}{\rho_W}\frac{C}{D}V\frac{dz}{dt} - g = -C_2 V U_z - g \qquad [5]$$

Where *x*, *y*, *z* are coordinates referring to the ground (with origin at the sprinkler nozzle), *t* is the time, *dx*/*dt*, *dy*/*dt*, *dz*/*dt* are components of *U*, ρ_W is the density of the water and *A* is the acceleration of the drop in the air. According to Vories et al. (1987), wind speed over an infinite plane varies logarithmically in the vertical direction as follows:

$$W_z = W_a \frac{\ln\left(\frac{z-d}{z_0}\right)}{\ln\left(\frac{z_a-d}{z_0}\right)} \qquad [6]$$

Where W_z is the wind speed at height z; W_a is the wind speed measured at a reference height over the ground z_a (in agrometeorology usually $z_a = 2$ m); d is the roughness height and z_0 is the roughness parameter. The parameters d and z_0 can be related to crop height (Stanhill, 1969; Tanner and Pelton, 1960).

Due to the complex sprinkler jet process, the following simplifications have been considered in these models: 1) the jet is disintegrated at the nozzle exit into individual drops with different diameters, moving independently in the air; 2) the drag coefficient is independent of the sprinkler height over the soil surface, the vertical jet angle, the wind velocity and the nozzle diameter; and 3) different-sized drops fall at different distances.

Von Bernuth (1988) divided researchers developing ballistic simulation models in two groups. The first group assumed that the air drag coefficient is a function of droplet size only (Seginer 1965; Von Bernuth and Gilley 1984; Hills and Gu 1989); while the second group assumed it to be a function of the velocity in the air and the droplet size (Fukui et al., 1980; Vories et al., 1987; Seginer et al., 1991; Kincaid, 1996).

The ballistic approach requires a preliminary determination of drop size distribution for a given sprinkler and a set of operating conditions. Fukui et al. (1980) and von Bernuth and Gilley (1984) presented a simulation scheme based on obtaining drop size distributions from the sprinkler radial water curve for a given sprinkler-pressure combination under no-wind conditions. Li et al. (1994) proposed the following empirical model to fit the drop diameter distribution curve:

$$P_V = \left(1 - e^{-0.693\left(\frac{D}{D_{50}}\right)^n}\right)100 \qquad [7]$$

Where: D is the drop diameter; P_v is the percent of total discharge in drops smaller than D; D_{50} is the mean drop diameter, and n is a dimensionless exponent. The values of D_{50} and n can be estimated as:

$$D_{50} = a_d + b_d R \qquad [8]$$

and

$$n = a_n + b_n R \qquad [9]$$

Where a_d, b_d, a_n, b_n are empirical coefficients and R is the ratio of nozzle diameter to pressure. Kincaid et al. (1996) presented experimental values of these parameters for a number of sprinkler types and nozzle diameters.

A considerable improvement in sprinkler irrigation simulation performance under windy conditions was obtained by introducing in the model empirical parameters to adjust the air drag coefficient as proposed by Seginer et al. (1991) and Tarjuelo et al. (1994). This adjustment is expressed by the following equation:

$$C' = C\left(1 + K_1 sin\beta - K_2 cos\alpha\right) \qquad [10]$$

Where: α is the angle formed by vectors V and W, β is the angle formed by the vectors V and U, and K_1 and K_2 are empirical parameters. The corrector coefficient K_1 narrows the water distribution pattern symmetrically in the direction perpendicular to the wind, while K_2 displaces the wetted area in the wind direction, shortening the distance from the centre of the wetted area to the sprinkler (windward direction) and lengthening more behind (leeward direction). The combination of both parameters has led to significant improvements in the simulation of wind distorted water distribution patterns (Tarjuelo et al, 1994). According to Montero et al. (2001), K_2 is much less relevant than K_1.

DESCRIPTION OF THE COUPLED SIMULATION MODEL (*AdorSim*)

The AdorSim model was programmed using the C++ language. The model is composed of two principal modules: a crop simulation module and a solid set sprinkler irrigation simulation module (hereafter designated as Ador-Crop and Ador-Sprinkler, respectively). The fact that both modules interchange information during their execution required writing new, specific source code. Significant changes were introduced in both modules respect to previous models. Several additional Ador modules perform data input and output operations. Ador is a Spanish acronym for "Decision Support Tool on Irrigation Organization". A research project is currently underway in our research group to develop comprehensive management and simulation software covering the irrigation, soils, crops and environmental aspects of both surface and sprinkler irrigated agriculture.

Ador-Crop development

The Ador-Crop module is similar to the well-known CropWat model (Smith, 19

93) in many aspects. The main differences between the two crop models are: 1) CropWat uses monthly meteorological data and four interpolation models to convert monthly ET_0 values to daily values, whereas Ador-Crop uses daily meteorological data, including daily ET_0; 2) CropWat computes the crop growth phases using the day as unit of time, while Ador-Crop uses degree-days; and 3) Ador-Crop simulates yield reduction at each cell i of a square grid defined within the sprinkler spacing. The irrigation module simulates the water applied at the center of each cell. In this way the spatial variability of irrigation water results in a spatial variability of soil water and therefore crop yield.

The Ador-Crop model is based on the model proposed by Stewart et al. (1977), where actual crop evapotranspiration (ET_a) and yield (Y) are normalized according to their maximum values (Eq. 1). Crop phenological development is divided into the vegetative, flowering, and grain filling stages based on thermal time (t_d) as defined by Gallagher (1979) in the following equation:

$$t_d = \sum_{i=1}^{n} (\overline{T_a} - T_b) \qquad [11]$$

Where $\overline{T_a}$ is daily mean air temperature, T_b is the base temperature at which development stops, and n is the number of days of temperature observation used in the summation.

Reductions in yield due to soil water stress were divided in four crop development stages using a different K_y for each stage. Cumulative yield reduction is determined using the following multiplicative formula:

$$\frac{y_i}{y_{\max}} = \prod_{f=1}^{4} \left[1 - k_{yn} \left(1 - \frac{ET_{ai}}{ET_m} \right)_n \right] \qquad [12]$$

Where f is the growth stage.

Just like in most functional models, all the soil water fluxes are considered one-dimensional (vertical). The soil is described as a single reservoir, characterized by its soil water content (SWC_{ij}), varying for each day (j) and cell within the sprinkler spacing (i) as follows:

$$\mathrm{SWC_{ij}} = \mathrm{SWC_{ij-1}} + \mathrm{P_j} + \mathrm{ID_{ij}} - \mathrm{ETa_{ij}} - \mathrm{Dp_{ij}} \qquad [13]$$

Where SWC_{ij-1} is the soil water content of square i on day j-1; P_j is the precipitation; ID_{ij} is the applied irrigation depth; ETa_{ij} is the actual crop evapotranspiration and Dp_{ij} is the deep percolation. Drainage occurs if SWC_{ij} is greater than the Total Available Water of cell i (TAW_i). During crop growth TAW increases linearly with the rooting depth (from initial root depth to maximum root depth).

The procedures used for the calculation of crop evapotranspiration, crop water requirements and irrigation requirements are based on FAO methodologies (Allen et al., 1998). Daily crop evapotranspiration (ETc_j) was estimated from daily values of reference evapotranspiration (ET_{0j}) calculated using the FAO Penman-Monteith equation, and from tabulated crop coefficients (K_c) following the FAO approach (Allen et al., 1998). The actual crop evapotranspiration, ETa_{ij} is given by:

$$\mathrm{ETa}_{ij} = \mathrm{ETc}_j \; ; \quad \mathrm{If\,SWD}_{ij\text{-}1} < \mathrm{AWD} \qquad [14]$$

$$\mathrm{ETa}_{ij} = \mathrm{ETc}_j \left(\frac{\mathrm{TAW}_i - \mathrm{D}_r}{(1-\mathrm{P})\mathrm{TAW}_i} \right); \quad \mathrm{If\,SWD}_{ij\text{-}1} > \mathrm{AWD} \qquad [15]$$

Where SWD_{ij-1} is the soil water depletion of cell i and in day $j-1$; AWD is the allowable water depletion limit, D_r is the root zone depletion and P is the fraction of TAW_i that a crop can extract from the root zone without suffering water stress.

Ador-Sprinkler development

Ador-Sprinkler uses ballistic theory to predict the path of each individual drop of water emitted by the sprinkler nozzles. The model calculations consist on 1) simulating a single sprinkler water distribution for a given wind condition; 2) overlapping a number of sprinklers at a given sprinkler spacing; and 3) determining water application depth in a user defined square grid of cells within a sprinkler spacing.

The drop size distribution corresponding to a given combination of sprinkler manufacturer, nozzle diameter and operating pressure can be determined using the empirical model proposed by Li et al. (1994) (Eq. 7, using D_{50} and n as empirical parameters). The air drag coefficient (C) for isolated drops is expressed as a function of the Reynolds number of a spherical drop (Fukui et al. 1980; Seginer et al. 1991). Finally, a fourth order Runge-Kutta numerical integration technique (Press et al., 1988) is used to solve the differential equations for drop movement and to determine the landing point for each drop. A total of 32,400 drops are used in each simulation, combining 180 different drop diameters (ranging from 0.2 to 7 mm), and 180 initial horizontal angles. At the end of this phase, the water application pattern of an isolated sprinkler is simulated.

The D_{50} and n model parameters need to be calibrated using no-wind experiments with an isolated sprinkler in order to reproduce the resulting water application pattern. To obtain the best combination of model parameters, two indexes are used for the comparison between measured and simulated water application: the Root Mean Square Error (*RMSE*) and the coefficient of correlation (*r*):

$$RMSE = \frac{1}{n_c\ t}\sqrt{\sum_{i=1}^{n_c}\left(ID_{mi} - ID_{Si}\right)^2} \qquad [16]$$

$$r = \frac{\sum\left(ID_{mi} - \overline{ID_m}\right)\left(ID_{Si} - \overline{ID_S}\right)}{\left(n_c - 1\right)S_m S_S} \qquad [17]$$

Where t is the duration of the irrigation event; n_c is the number of catch cans; ID_{mi} and ID_{Si} are the catch can values of measured and simulated irrigation depth; $\overline{ID_m}$ and $\overline{\mathrm{ID}_S}$ are the average measured and simulated irrigation depths; and S_m and S_s are the standard deviation of measured and simulated *ID*. The optimum values of D_{50} and n are those resulting in minimum *RMSE* and maximum *r*.

Empirical equations are used in Ador-Sprinkler to estimate wind drift and evaporation losses (*WDEL,* %). The drop size distribution curve is corrected in each simulation run to account for *WDEL*. As a result, the value of P_v for the largest simulated drop diameter passes from 100 % to 100 – WDEL %. For this correction, the procedure proposed in the *SIRIAS* model (Montero et al., 2001) as option B is used. Drift losses are considered proportional to the volume of water collected in each point of the radial curve, while evaporation losses are considered inversely proportional to the drop size. In the model, both types of losses account for the same amount of water.

In order to simulate solid set sprinkler irrigation, 18 sprinklers are used in the model, and their water application is overlapped. Sprinkler co-ordinates are determined by the model to adjust to the user specified distance between sprinklers and sprinkler lines. The sprinkler spacing is divided into a square grid, with the number of cells equal to the number of simulated catch cans. The irrigation depth at each cell is determined from the number of drops landing in the cell, their diameter, the drop size distribution curve and the sprinkler discharge (determined from the nozzle diameters and the operating pressure).

Irrigation performance parameters such as the Christiansen Coefficient of Uniformity (*CU*, %) can be computed from the irrigation depth at the cells:

$$CU = \left(1 - \frac{\sum_{i=1}^{n_c} \left| ID_i - \overline{ID} \right|}{n_c \, \overline{ID}} \right) 100 \qquad [18]$$

A new phase of model calibration is required at this point, since adequate values for K_1 and K_2 must be identified. Field experiments are used to determine water application in a square catch can grid within a sprinkler spacing under wind conditions. The comparison between measured and simulated irrigation depths is established in terms of the two above-mentioned indexes (*RMSE* and *r*), and an additional index: the absolute difference between the measured and simulated *CU* (CU_{abs}, %). The optimum values of K_1 and K_2 result in minimum CU_{abs}, minimum *RMSE* and maximum *r*. When this calibration procedure is repeated for different wind conditions, different values for K_1 and K_2 are typically found. A functional relationship can be established between the wind speed and the values of K_1 and K_2. This puts an end to the calibration phase. The optimal values of D_{50}, *n*, $K_1(W)$ and $K_2(W)$ can be applied to the simulation of any wind condition, irrigation duration, crop height and sprinkler spacing of the calibrated sprinkler, nozzles, and operating pressure.

Model input and output

Figure IV.1 shows a functional diagram of AdorSim. The figure reflects the relationship between data types and between the two main simulation modules. Ador-Sprinkler input data include:

1. Characteristics of the irrigation system:
    a. Solid-set sprinkler irrigation setup: vertical angle of the sprinkler jet (º), diameter of the sprinkler nozzle(s) (mm), nozzle height (m), nozzle pressure (kPa), azimuth of the sprinkler line (º), type of solid set (triangular vs. rectangular), sprinkler spacing (inside a line and between lines, m), and number of simulated catch cans.
    b. Calibration parameters (d_{50}, *n*, K_1 and K_2).

2. Meteorological data: wind sensor measurement height (m), and 30-min averages of wind speed (m s^{-1}) and direction (º), air temperature (ºC) and air relative humidity (%).
3. Crop data: crop height (m), obtained from Ador-Crop.

Ador-Crop input data include:

1. Daily meteorological data: precipitation (mm), maximum and minimum air temperature (ºC), average air relative humidity (%), average wind speed (m s^{-1}) and ET_0 (mm).
2. Crop parameters: base temperature (ºC), temperature sum for each phenological stage, minimum and maximum rooting depth, allowable water depletion, crop coefficients for potential ET calculation, and crop response factors to water stress.
3. Soil characteristics: soil depth, *TAW* and initial soil water depletion at each simulated catch can. These data represent the soil spatial variability within the sprinkler spacing area.
4. Irrigation data: irrigation depth at each simulated catch can resulting from each irrigation event.

The daily calculations of Ador-Crop start with an irrigation decision routine. Irrigation can be performed following preset irrigation dates an times. In this work, this option will be used at the calibration and validation phases. In the companion paper, an irrigation scheduling routine will be applied to determine the irrigation date and time, including the irrigation duration. In that case, in a context of variable wind speed and direction, the irrigation criteria will try to avoid irrigating under unfavourable conditions.

Model output includes irrigation depth at each catch can for each irrigation event, water balance and crop yield reduction at each cell, irrigation performance indexes (such as *CU* and *WDEL)*, and field average yield reduction and deep percolation losses.

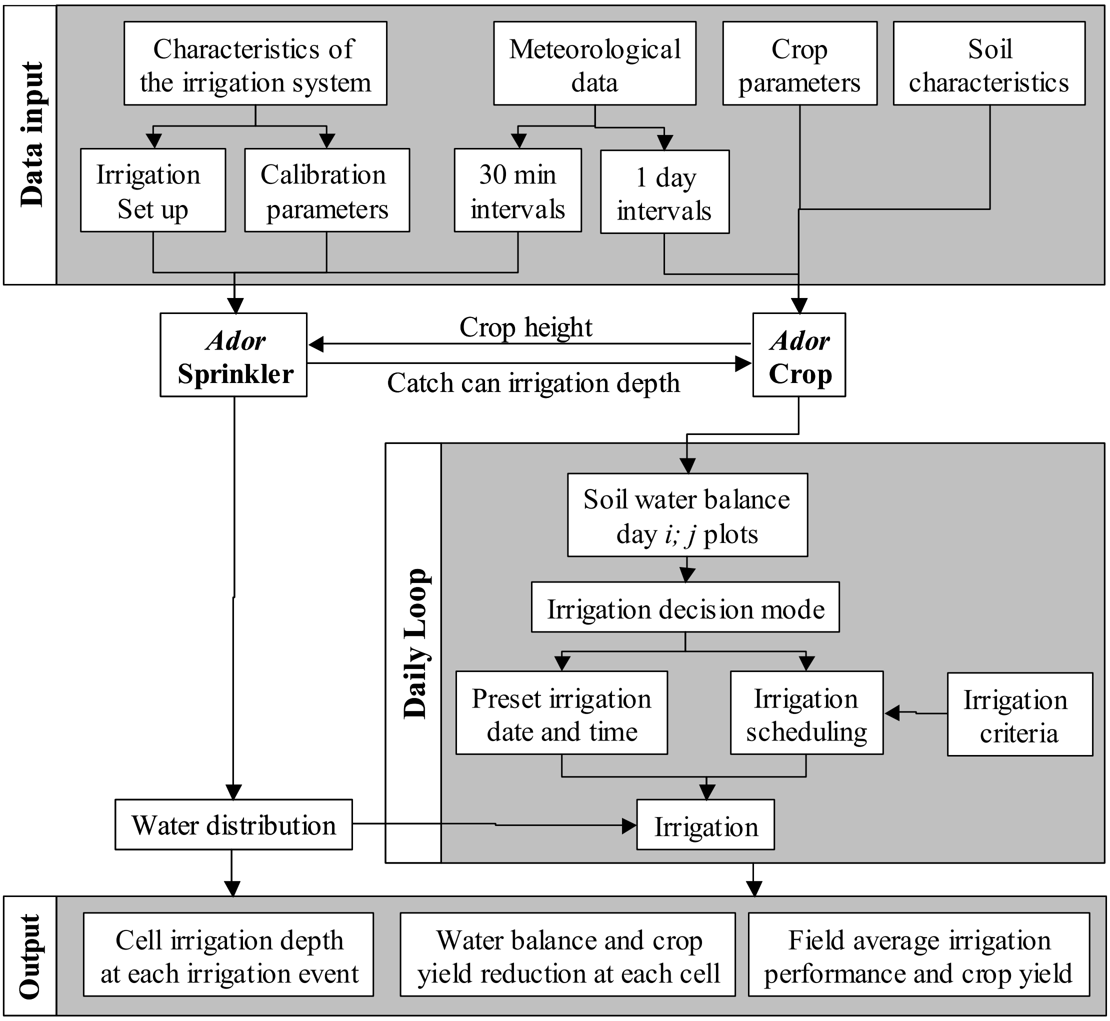


Figure IV.1. *Schematic description of the AdorSim model.*

Figura IV.1. *Descripción esquemática del modelo AdorSim*

FIELD EXPERIMENTS

Two field experiments were performed in the summer of 2000 at the experimental farm of the Agricultural Research Service of the Government of Aragón in Zaragoza, Spain (41° 43´N, 0°48´W, 225 m of altitude) to calibrate and validate the coupled model. The first experiment consisted on a field irrigation evaluation of an isolated sprinkler under no-wind conditions and high air relative humidity. The sprinkler type was "VYR 70", manufactured by VYRSA (Briviesca, Burgos, Spain), the nozzle diameters were 4.4 mm and 2.4 mm, and the nozzle operating pressure was 300 kPa. This experiment allowed to characterize water application pattern for the sprinkler-nozzle-pressure combination used in the field experiment. Catch cans spaced at 0.5 m were installed along four radii extending from the isolated sprinkler. This experiment was designed to calibrate the parameters of the drop size distribution curve.

The second experiment was performed on a solid set sprinkler irrigation system arranged in a triangular spacing of 18 m by 15 m. This solid set was used to irrigate a corn crop (*Zea mays* L. cv. Dracma). The sprinkler material and operating pressure were as described in the first experiment. The duration of the corn phases was derived from the measured phenological data. A detailed description and analysis of this second experiment can be found in chapter III. The objective of this second experiment was to provide experimental data for the calibration of the K_1 and K_2 parameters, and to validate the crop and solid set irrigation models.

Irrigation was scheduled to fulfill corn water requirements during all growth stages. A total of 24 irrigation events were applied. Irrigation evaluations were performed in 23 irrigation events using the methodology proposed by Merriam and Keller (1978) and Merriam et al. (1980) in two sprinkler spacings identified as plots A and B (Figure IV.2). The first irrigation event of the season was not evaluated, although it was used for water budget in crop simulation. Corn yield was measured in 25 subplots of 1.5 m x 1.5 m, each of them with a catch can in the center.

Data from the evaluated irrigation events were used to derive the following predictive *WDEL* equation (see chapter III):

$$WDEL = 5.287W + 7.479 \qquad [19]$$

The meteorological data used for model input and for determining Penman-Monteith ET_0 were recorded during the crop season in an automated meteorological station (Campbell Scientific, Logan, Utah) installed over a 1.2 ha grass plot located at a distance of 200 m from the experimental plot. Wind speed (W) and direction (dW) were recorded with a frequency of 2 minutes, while the rest of meteorological data were recorded with a frequency of 30 minutes. Since the field irrigation evaluations used for model calibration were performed on corn and wind speed was recorded on grass, a correction was applied to the measured wind speed. For this purpose, the relationship between the wind speed measured at 2 m on grass and on corn (considering the different corn canopy heights) during the summer of 1997 in the same experimental farm were obtained by linear regressions.

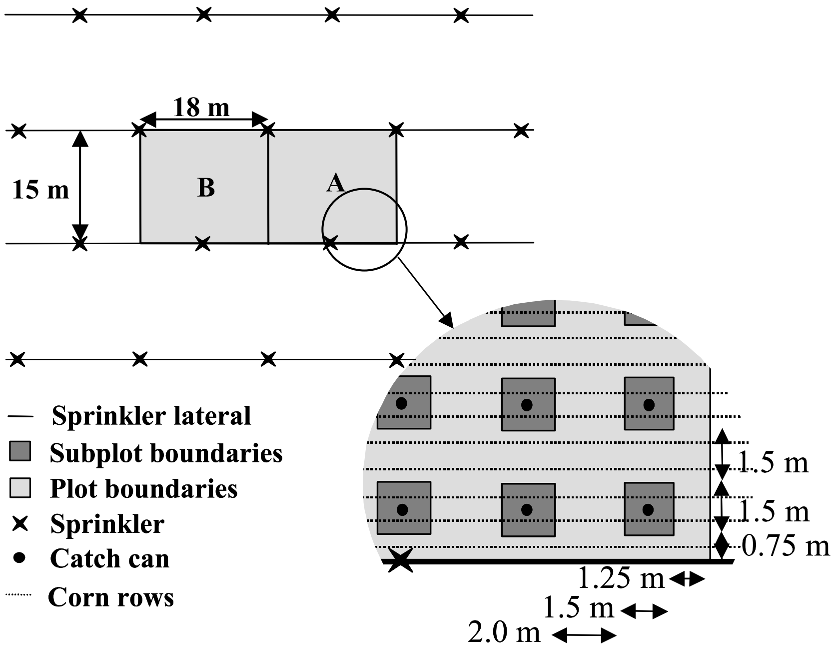


Figure IV.2. *Detail of field experiment describing the two experimental plots, the sub-plots, and the location of the sprinklers, catch cans and corn rows.*

Figura IV.2. *Detalle del experimento de campo describiendo los dos marcos, las parcelas y la localización de los aspersores, pluviómetros e hileras del cultivo.*

For model calibration and validation purposes, the irrigation depths (*IDc*) measured after each irrigation event in catch cans located at the same position in plots A and B were averaged and assigned as the measured *IDc* of the corresponding sub-plot. The measured yield reduction (*YR*) of each sub-plot of both plots was calculated as the difference between 100 and the percentage of grain yield (*GY*) to maximum *GY* (see chapter III).

The statistical significance levels considered in the regression analyses were: "*ns*" to indicate non significant ($P > 0.05$); "*" to indicate $0.05 \geq P > 0.01$; "**" to indicate $0.01 \geq P > 0.001$; and "***" to indicate $0.001 \geq P$.

CALIBRATION AND VALIDATION OF ADOR-SPRINKLER

Determination of the drop size distribution parameters D_{50} and *n*

The adjustment of the drop size distribution parameters was performed comparing the observed and simulated water distribution patterns for the combination of nozzle size and operating pressure used in the first experiment. The Ador-sprinkler model was run for 272 combinations of D_{50} and *n*. In these model runs the value of D_{50} ranged from 0.8 mm to 1.55 mm, with an increment of 0.00005 m, while the value of *n* ranged from 2.0 to 2.8, with an increment of 0.05. The optimum parameter combination was $D_{50} = 1.30$ mm and $n = 2.50$ (*RMSE* of 0.48 mm h^{-1} and r of 0.794). The application of the predictive drop size parameter equations proposed by Kincaid et al. (1996) (Eqs. 7, 8 and 9) to the experimental conditions yielded the following results: $D_{50} = 2.05$ mm, and $n = 1.82$. When these values were supplied to Ador-Sprinkler and the resulting water distribution pattern was compared to the experimental results, the similitude indexes worsened: $RMSE = 0.874$ mm h^{-1} and r = 0.446. This poor performance can be attributed to a number of facts, some of which were already identified by Seginer et al. (1991): 1) the difference between the sprinkler and nozzle manufacturers used by Kincaid et al. (1996) and ourselves; 2) possible model inaccuracies in areas such as the air drag coefficient; 3) the fact that Kincaid et al. (1996) performed indoor experiments, while we did outdoor tests, subjected to WDEL (8.6 % in the experimental conditions).

Selection of the optimum values of K_1 and K_2

In Ador-Sprinkler only one value of *W* and *Wd* is used for each simulation. In order to consider the variation of these meteorological variables during a given irrigation event, each event was subjectively divided in partial irrigations. The wind direction was divided in eight classes of 45º each, plus an additional class for calm conditions in which no corrections were required on the air drag coefficient *C*. Each partial irrigation was characterized by: 1) Its duration; 2) Average wind speed; and 3) Weighted average wind direction recorded in the dominant class.

Seven irrigation events, reflecting a wide range in wind speed, were used for the calibration process (Table IV. 1). For each partial irrigation a total of 300 simulations were performed, with the value of K_1 ranging from 0.0 to 2.8 (with an increment of 0.2) and the value of K_2 ranging from 0.00 to 0.95 (with an increment of 0.05). The catch can irrigation depth resulting from each simulated partial irrigation was accumulated to obtain the total catch can irrigation depth for each irrigation event. Figure IV.3 presents the CU_{abs}, *RMSE* and *r* values obtained with each combination of K_1 and K_2 for four of the calibration irrigation events, numbered 17, 7, 8 and 22. The corresponding average wind speeds were 0.8, 2.6, 4.2, and 6.2 m s^{-1}, respectively.

Results show that for a wind speed of 0.8 m s^{-1}, the optimum value of *r* occurred in a different area than for *CUabs* and *RMSE*. For the other three wind conditions the optimum values of the three parameters are approximately coincident, and adequate values of K_1 and K_2 could be selected that are close to satisfying all these similitude criteria. The optimum K_2 values increase linearly with wind speed. The optimum K_1 values increase from 0.8 m s^{-1} to a value between 2.6 m s^{-1} and 4.2 m s^{-1}, to decrease again for a wind of 6.2 m s^{-1}. Tarjuelo et al. (1994) identified a different relationship between the magnitude of the correction parameters and the wind speed. Montero et al. (2001), in their calibration of the SIRIAS model, found no relationship between wind speed and the magnitude of the correction parameters.

According to these observations, the selection of the optimum K_1 and K_2 values was performed as follows: 1) For each irrigation event with average wind speed above 2.1 m s^{-1}, a parameter combination satisfying *RMSE* and *r* was selected; 2) *CUabs* was only considered if more than one optimum combination of K_1 and K_2 could be identified (in this case, the set of parameters yielding the minimum value of *RMSE* x CU_{abs} was selected); and 3) In irrigation events with $W < 2.1$ m s^{-1}, the parameter combination yielding minimum *RMSE* x CU_{abs} was selected. The points identified with a cross in Figure IV.3 represent the selected values of the parameters. Considering the selected parameters in all seven calibration irrigation events, the following relationship between K_2 and *W* was determined:

$$\begin{aligned}&for\ \ W \le 1.1\,ms^{-1}; \quad K_2 = 0\\ &for\ \ W > 1.1\,ms^{-1}; \quad K_2 = 0.0719W - 0.0814, \qquad (R^2 = 0.985^{***}) \qquad [20]\end{aligned}$$

Table IV.1. *Characteristics of the 23 evaluated irrigation events used for calibration and validation of the Ador-Sprinkler model. The data include: duration of the irrigation event [t], catch can elevation above soil surface [Cce], Average wind speed [W], dominant wind direction [WD], Percent of irrigation duration during which the dominant wind direction was recorded [tWD], number of wind direction classes [#WDc], Root Mean Square Error [RMSE] between the irrigation depth collected plots A and B for each catch can, and Average Christiansen Coefficient of Uniformity of plots A and B [CU]. The character "c" indicates that the irrigation evaluation was used for model calibration.*

Tabla IV.1. *Características de los 23 riegos evaluados usados para la calibración y la validación del modelo Ador-Sprinkler. Se presenta: la duración del riego [t], la elevación de los pluviómetros sobre el suelo [Cce], la velocidad del viento media [W], la dirección del viento dominante [WD], el porcentaje del tiempo de riego en el que la dirección del viento coincidió con la dominante [tWD], el número de clases de dirección del viento [#WDc], la raíz cuadrada del error cuadrático medio [RMSE] entre la dosis de riego recogida en los pluviómetros de los marcos A y B, y el promedio del coeficiente de uniformidad de Christiansen [CU] de los marcos A y B. El carácter "c" indica que este riego fue usado para la calibración del modelo.*

# Irrigation	t (h)	Cce (m)	W (m s^{-1})	WD (°)	tWD (%)	# WDc (-)	RMSE (mm h^{-1})	CU (%)
IE1	3.0	0.36	4.8	90-135	86	3	1.27	64.8
IE2	7.0	0.36	3.2	225-270	88	3	0.64	74.8
IE3	6.0	0.36	1.4	225-270‡	23	8	0.40	93.9
IE4-***c***	2.0	0.36	2.7	180-225	51	3	0.92	81.5
IE5	5.0	0.36	1.1	135-180‡	38	8	0.55	94.3
IE6-***c***	3.0	0.36	2.0	90-135‡	46	8	0.62	87.6
IE7-***c***	2.0	0.75	2.6	135-180	44	4	0.52	81.3
IE8-***c***	5.0	0.75	4.2	315-360	58	4	0.75	75.0
IE9	4.1	1.50	5.3	315-360	64	2	1.13	54.7
IE10	4.0	1.50	1.2	135-180	47	6	0.39	91.6
IE11	6.0	1.50	2.4	180-225	51	5	0.44	73.7
IE12	3.9	1.50	0.6	0-45	35	6*	0.39	92.8
IE13	6.0	1.50	3.1	135-180	43	6	0.51	70.3
IE14	6.0	1.50	6.5	315-360	62	2	1.15	56.4
IE15-***c***	3.2	1.50	1.1	135-180	100	1	0.39	93.9
IE16	5.5	2.16	1.3	0-45	47	6*	0.50	87.1
IE17-***c***	4.2	2.16	0.8	0-45	63	3*	0.63	88.1
IE18	4.0	2.16	1.2	45-90	44	6*	0.40	86.1
IE19	3.0	2.16	0.6	45-90	42	7*	0.51	89.0
IE20	3.0	2.16	0.7	0-45	40	5*	0.45	90.1
IE21	5.0	2.16	1.0	0-45‡	48	8*	0.63	88.0
IE22-***c***	5.0	2.16	6.2	270-315	53	3	0.79	54.3
IE23	4.0	2.16	1.8	225-270‡	36	8	0.41	80.8
Average		-	2.4	-	-	-	0.63	80.5

‡ A dominant wind direction was established, but wind blew from all directions during the irrigation event.

* Calm periods were recorded during the irrigation event.

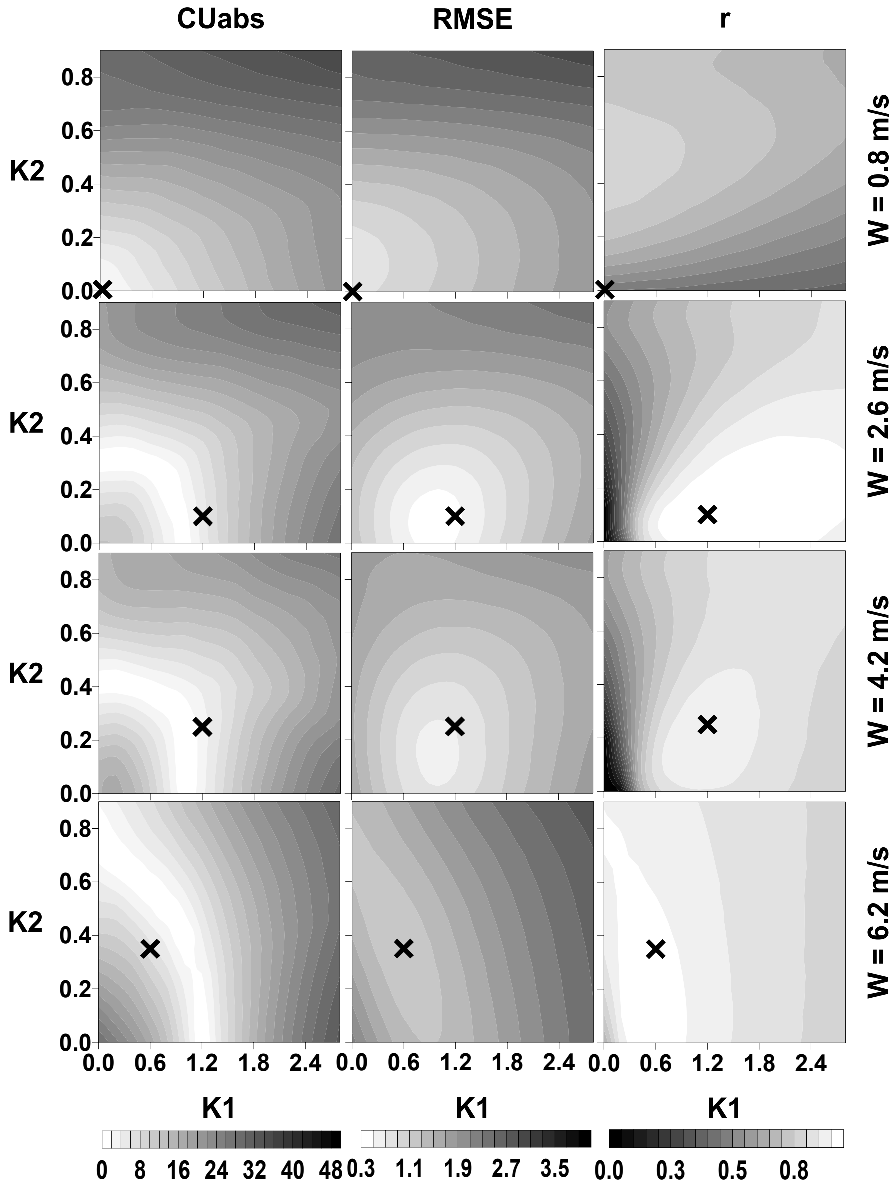


Figure IV.3. *Absolute difference between the measured and simulated CU [CU_{abs}], Root Mean Square Error [RMSE] and coefficient of correlation [r] obtained with each combination of K_1 and K_2 during the Ador-Sprinkler calibration process. Results are presented for four irrigation events characterized by different wind speeds (0.8 m s^{-1}, 2.6 m s^{-1}, 4.2 m s^{-1} and 6.2 m s^{-1}). Crosses indicated the selected combination of K_1 and K_2 for each case.*

Figura IV.3. *Valor absoluto de la diferencia entre la uniformidad medida y simulada [CU_{abs}], la raíz cuadrada del error cuadrático medio [RMSE] y el coeficiente de correlación [r] obtenidos para cada combinación de K_1 y K_2 durante la fase de calibración de Ador-Sprinkler. Los resultados se presentan para cuatro riegos caracterizados por diferentes velocidades de viento (0,8 m s^{-1}, 2,6 m s^{-1}, 4,2 m s^{-1} y 6,2 m s^{-1}). En cada caso, las cruces indican los valores seleccionados de K_1 y K_2.*

Since the variation of K_1 with W did not follow a linear trend, fixed values of K_1 were considered for four wind speed ranges. The optimal values of K_1 were 0.0, 1.0, 1.2 and 0.6 for wind speeds below 1.5 m s^{-1}, between 1.5 and 2.1 m s^{-1}, between 2.1 and 4.5 m s^{-1} and above 4.5 m s^{-1}, respectively. For wind speeds below 1.1 m s^{-1}, the correction of the aerodynamic drag coefficient C was not required.

Ador-Sprinkler validation

Two types of model validation were performed using the optimum values of K_1 and K_2 obtained during the calibration process; partial and complete irrigations. The simulation input data for the complete irrigation events consisted of: 1) the average values of wind speed, air temperature and relative humidity recorded during the irrigation event; and 2) the weighed wind direction corresponding to the class in witch the recorded wind direction was most frequent (Table IV.1). The seven irrigation events used for model calibration were not considered in the validation process. The experimental *CU*'s for each irrigation event were compared with the simulated values (partial and complete irrigation events) (Figure IV.4). Model validation was satisfactory in both cases, since the slopes and intercepts of the regression line were not significantly different from 1 and 0, respectively (P = 0.95), and both coefficients of determination were higher than 0.793***. The differences between partial and complete irrigation events are small, but complete irrigation events produced better validation results (R^2 = 0.871***).

Concerning water distribution, the *RMSE* for complete irrigation events varied from 0.48 mm h^{-1} to 2.11 mm h^{-1}, with an average of 0.95 mm h^{-1}. When partial irrigation events were simulated, the *RMSE* varied from 0.44 mm h^{-1} to 3.95 mm h^{-1}, with an average of 1.22 mm h^{-1}. Even if these *RMSE* values were somewhat higher than the *RMSE* between the measured water distributions in plots A and B (Table IV.1), a relevant part of the calibration error corresponded to experimental errors. It can be concluded that the model offered an appropriate prediction of water distribution under the experimental operating conditions. Since the simulation with complete irrigation events was slightly better and is simpler to implement, this was the procedure used in the rest of this work.

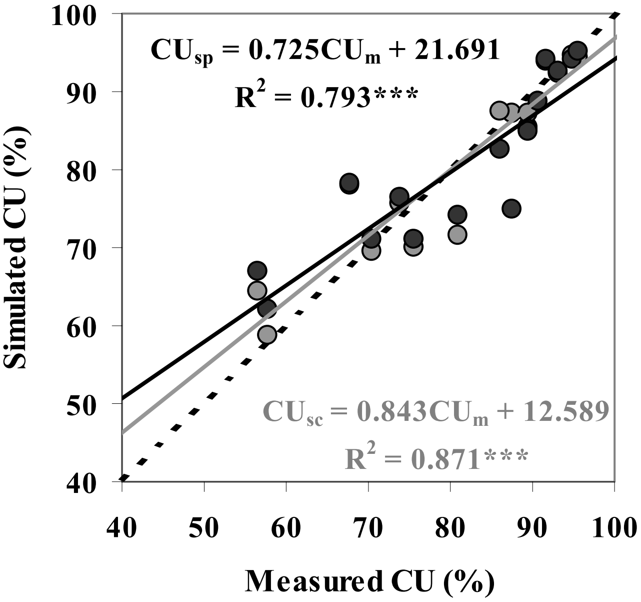


Figure IV.4. *Relationship between measured [CU$_m$] and simulated [CU$_s$] CU considering partial irrigation events [CU$_{sp}$] and complete irrigation events [CU$_{sc}$]. The dotted line represents the 1:1 relationship. The black dots and black regression line correspond to CU$_{sp}$, while the grey dots and grey regression line correspond to CU$_{sc}$.*

Figura IV.4. *Relación entre los valores de CU medidos [CU$_m$] y simulados [CU$_s$] considerando riego parciales [CU$_{sp}$] y completos [CU$_{sc}$]. la línea de puntos representa la línea 1:1. Los puntos negros y la recta de regresión negra corresponden a CU$_{sp}$, mientras que los puntos grises y la recta de regresión gris corresponden a CU$_{sc}$.*

VALIDATION OF ADOR-CROP

Comparison with CropWat

In order to test the Ador-crop simulation module, a comparison with CropWat (Smith, 1993; Clarke et al., 1998) was performed. The crop parameters proposed in the CropWat software for corn were used in both models, except for the duration of the crop growth phases, which were derived from experimental phenological data, and the crop coefficients, which were calculated from the experimental data following the FAO approach in Allen et al. (1998). Both models were run using the measured soil characteristics (*TAW*, initial soil moisture depletion and maximum soil depth) at each sub-plot of both plots, and the measured catch can irrigation depths (*IDc*). A maximum soil depth of 0.9 m was considered because no soil water extraction was observed below that depth. CropWat *YR*'s were determined using the four proposed models for calculating the daily ET_0 values (Smith, 1993). CropWat1 corresponds to the ET_0 distribution model that fits a curve to monthly averages; CropWat2 corresponds to the model that fits a parabola to three-month averages; CropWat3 considers linear ET_0 distribution at the end of the month; and CropWat4 takes ET_0 monthly averages as daily values. For each case and sub-plot, the CropWat seasonal *YR* was determined using Eq. 12.

The regression of CropWat *vs.* Ador-Crop *YR* showed an adequate fit ($R^2 > 0.97$***) for all four CropWat variants (Figure IV.5). The regression intercepts and slopes were in all cases not significantly different from 0 and 1, respectively. The best fit was obtained when the ET_0 distribution model used to extrapolate daily values is a linear distribution at the end of the month (Figure IV.5c). Only the first case (Figure IV.5a) presents an Ador-crop simulated *YR* larger than that simulated with CropWat. This was due to the fact that during a great extent of the crop growth season the daily maximum ET considered in Ador-Crop was greater than that calculated with CropWat (Figure IV.6). As a consequence, soil water uptake and yield reduction simulated with Ador-Crop were larger than with CropWat. In the case of CropWat2, the contrary trend could be observed.

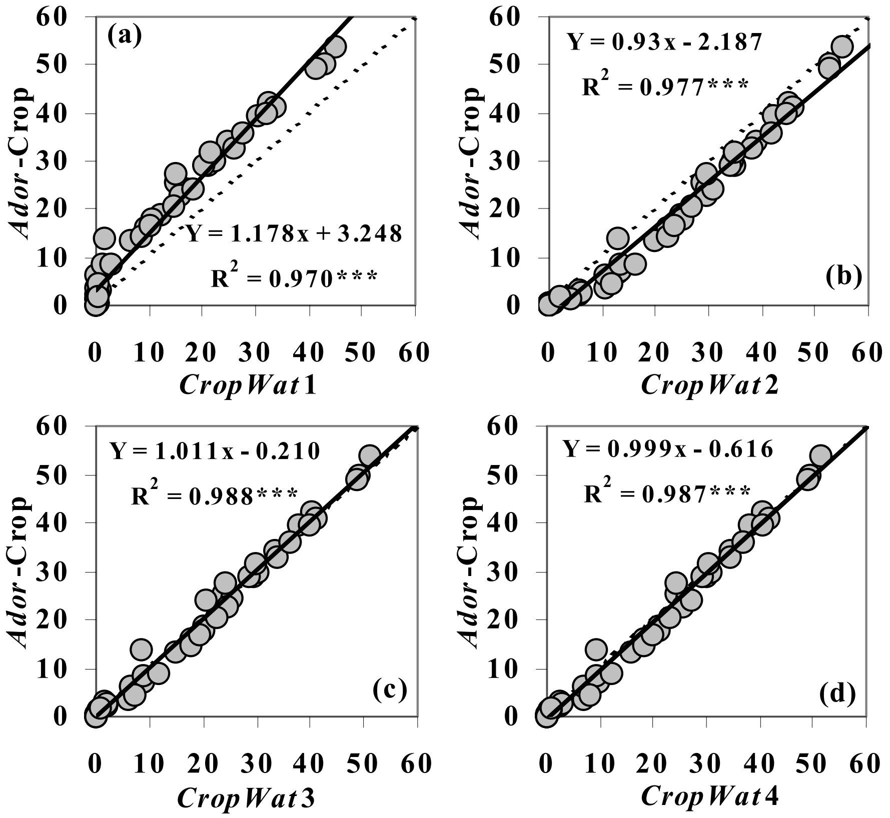


Figure IV.5. *Ador-Crop yield reduction (%) vs. CropWat yield reduction (%) using the ET_0 distribution model fitting: a) a curve to monthly averages (CropWat1); b) a parabola to three-month averages (CropWat2); c) a linear distribution at the end of the months (CropWat3); and d) monthly averages as daily values (CropWat4). The dotted line represents the 1:1 relationship. The equation and the solid lines correspond to the regressions.*

Figura IV.5. *Reducción de rendimiento simulada con Ador-Crop (%) vs. CropWat usando el modelo de distribución de ET_0 que ajusta: a) una curva a los valores mensuales (CropWat1); b) una parábola a los valores medios de tres meses (CropWat2); c) una distribución lineal en los extremos de los meses (CropWat3); y d) valores mensuales como valores medios (CropWat4). La línea de puntos representa la línea 1:1. Las ecuaciones y las rectas de regresión se corresponden con las cuatro variantes.*

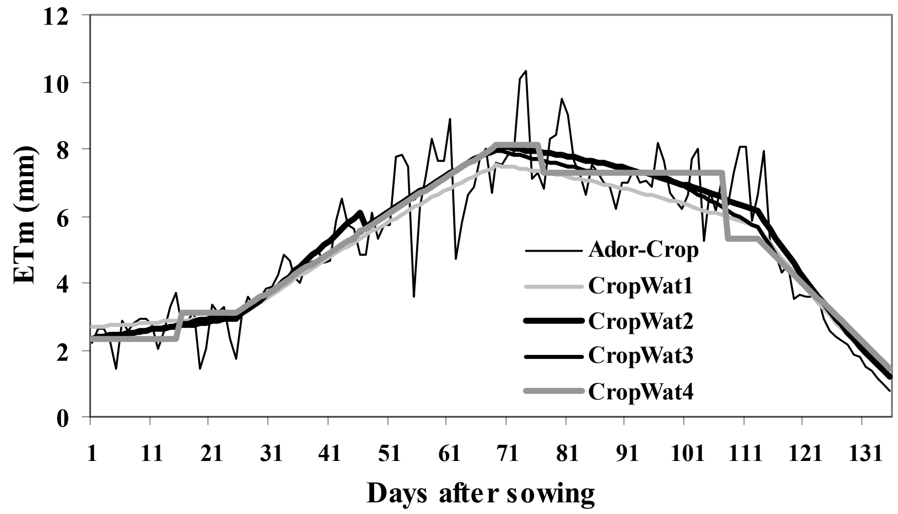


Figure IV.6. *Maximum evapotranspiration values [ETm] calculated with Ador-Crop and CropWat using the four ET_0 distribution models to calculate daily ET_0.*

Figura IV.6. *Valor máximo de la evapotranspiración [ETm] calculado con Ador-Crop y con CropWat usando los cuatro modelos de distribución de la ET_0 mensual para calcular la ET_0 diaria.*

Relationship between yield reduction and available water

The measured and simulated YR's corresponding to each sub-plot of both plots were plotted against the Seasonal Available Water (*SAW)*, determined as the initial soil available water plus irrigation and precipitation (Figure IV.7a). Twelve sub-plots (out of the total of 50) were not considered in this analysis because of their low plant density or because of low infiltration and water logging. A linear response was found between the simulated *YR* and *SAW* up to the value of the maximum seasonal evapotranspiration. Beyond this value, no yield reduction was observed. The scatter plot for measured *YR* represents the same trend as for simulated *YR* but with a larger variability. This variability determines that the relationship between measured and simulated *YR* (Figure IV.7b) is characterized by a poor coefficient of determination (R^2 = 0.378***).

The large variability of the measured *YR* could be related to other non water-related factors, such as soil fertility or mild irrigation water and soil salinity (see chapter III). Figure IV.8 illustrates the effect of additional factors on *YR*. While the scatter plot of *SAW* between the same subplots in plots A and B shows a good agreement (Figure IV.8a), the scattering of the corresponding plot for measured *YR* is high (Figure IV.8b).

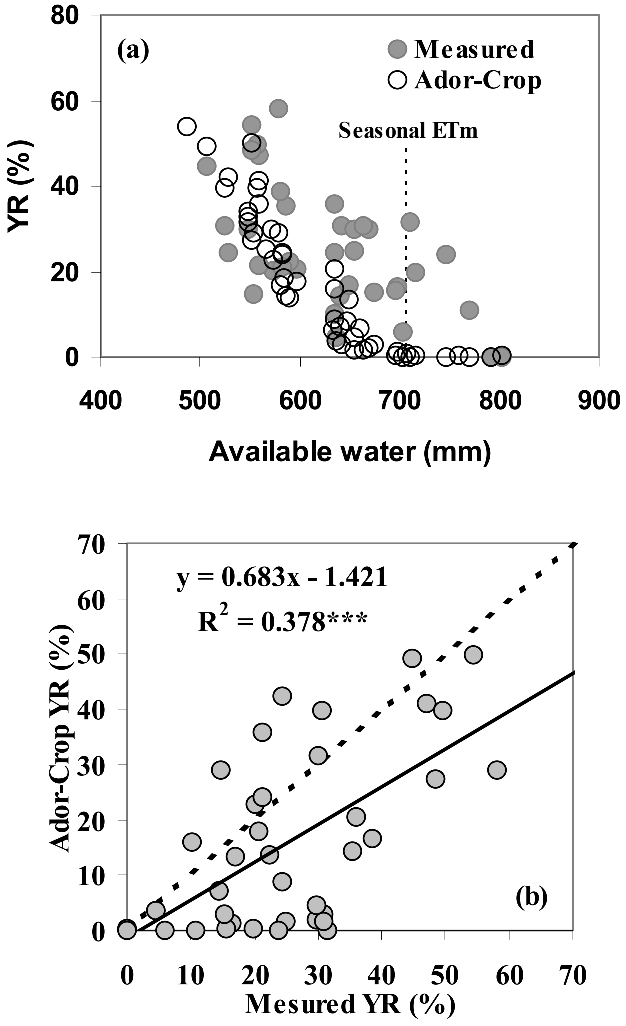


Figure IV.7. *Ador-crop validation: a) Relationship between the seasonal available water [SAW] for the crop and the yield reduction [YR] as measured and simulated with Ador-Crop; and b) Measured vs. Ador-Crop simulated yield reduction.*

Figura IV.7. *Validación de Ador-crop: a) Relación entre el agua total disponible estacional para el cultivo [SAW] y la reducción del rendimiento [YR], medida y simulada* *con Ador-Crop; and b) Valores de la reducción de rendimiento medidos vs. simulados con Ador-Crop*

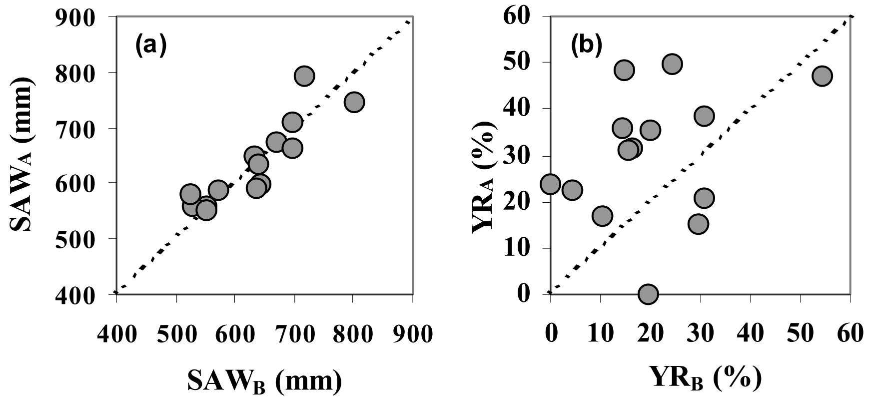


Figure IV.8. *Relationship between: a) seasonal available water measured in plots A [SAW_A] and B [SAW_B], and b) yield reduction measured in plots A [YR_A] and B [YR_B]. The dotted line represents the 1:1 relationship.*

Figura IV.8. *Relación entre: a) Agua estacional disponible medida en los marcos A [SAW_A] y B [SAW_B], y b) Reducción de rendimiento medida en los marcos A [YR_A] y B [YR_B]. La línea de puntos representa la línea 1:1.*

VALIDATION OF THE COUPLED MODEL ADORSIM

The first part of the validation consisted on reproducing Figure IV.7a. but using AdorSim instead of Ador-Crop. This implies using simulated *IDc* instead of measured catch can data. Figure IV.9a presents a scatter plot of measured *vs.* simulated seasonal catch can irrigation depth (ID_{CS}). The difference between the simulated and measured *IDcs* amounted to 13.1 mm, with respective standard deviations of 72.7 mm and 71.3 mm. The correspondence between these two variables is very high, and therefore the scatter plot between *SAW* and AdorSim simulated *YR* (Figure IV.9b) is very similar to what could be observed in Fig 7a.

The validation of the coupled model AdorSim proceeded with the comparison of the *YR*'s 1) simulated with the coupled model, 2) simulated with Ador-Crop using the measured irrigation depth (ID_C) as water input, and 3) measured in the field experiment. A regression analysis performed between both simulated *YR*'s (Figure IV.10a) indicated that the regression slope and intercept were not significantly different from 1 and 0, respectively. AdorSim slightly over estimated *YR*, and explained 73 % of the variability in Ador-Crop simulated *YR*. The difference between the average yield reductions simulated with both models was 2.92 % (corresponding to 292 kg ha^{-1} in the present case). The standard deviation of the simulated and measured *YR*'s were 17.9 % and 15.4 %, respectively. Finally, Figure IV.10b presents a scatter plot between measured and AdorSim simulated *YR*. AdorSim could explain 25 %** of the variability in measured *YR*, while Ador-Crop could explain 38 %***. The simulation of sprinkler irrigation introduces additional error in the model, but most of the scatter in the validation plot is due to the relevance of non water-stress related factors on *YR*.

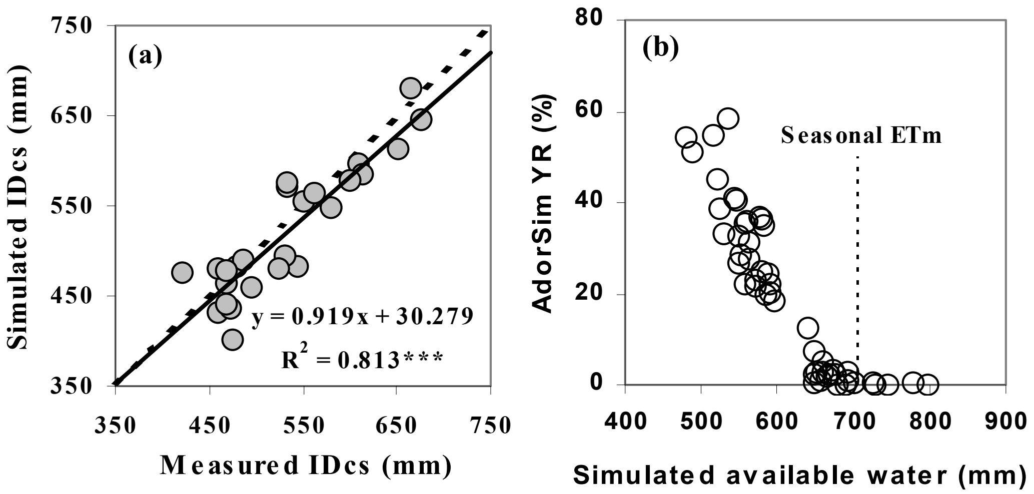
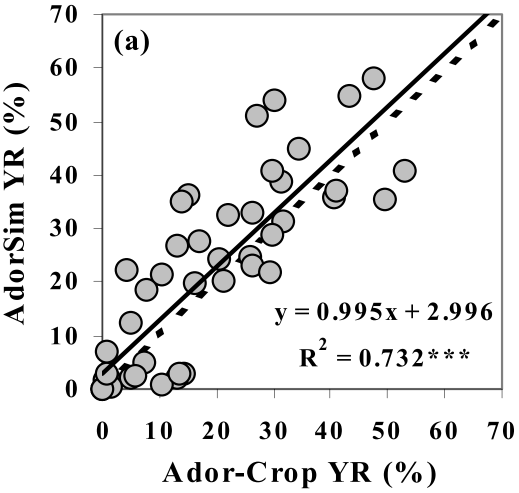


Figure IV.9. *Relationship between: a) simulated and measured seasonal irrigation depth [IDcs]; and b) Yield reduction [YR] calculated with Ador crop model using catch can irrigation depths as water input and yield reduction calculated with the coupled model AdorSim using simulated irrigation depth. The dotted line represents the 1:1 relationship.*

Figura IV.9. *Relación entre: a) Valores simulados y medidos de la dosis de riego recogida en los pluviómetros [IDcs]; y b) Reducción de rendimiento [YR] calculada con el modelo Ador-crop usando datos de dosis de riego medida en los pluviómetros como entrada de riego. La línea de puntos representa la línea 1:1.*



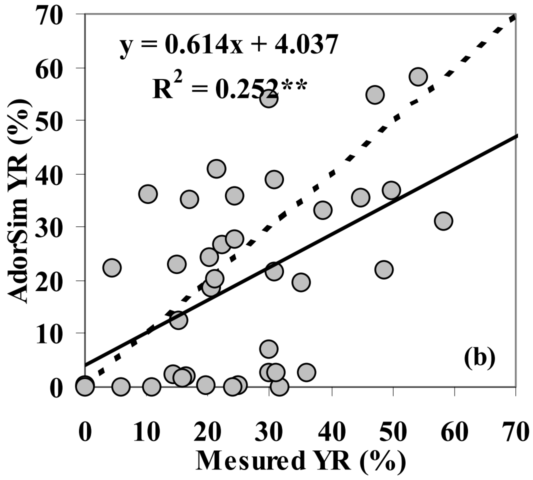


Figure IV.10. *AdorSim validation: a) Relationship between the seasonal available water [SAW] for the crop and the yield reduction [YR] as measured and simulated with AdorSim; and b) Measured vs. AdorSim simulated yield reduction.*

Figura IV.10. *Validación de AdorSim: a) Relación entre el agua estacional disponible para el cultivo [SAW] y la reducción de rendimiento [YR] medida y simulada con AdorSim; y b) Reducción de rendimiento medida vs. simulada con AdorSim*

In a similar simulation study analyzing a surface irrigation experiment performed in the same farm, Cavero et al., (2001) used a surface irrigation simulation model and the crop growth model EPICphase. The combination of both simulation approaches explained between 26 and 56 % of the variability in measured crop yield. In the present work, the use of a more complete crop growth model could have resulted in a better simulation of the measured crop yield. This circumstance will be explored in future works.

SUMMARY AND CONCLUSIONS

The simulation of solid set sprinkler irrigation under windy conditions is a complicated task due to the frequent variation of wind speed and direction during an irrigation event. The calibration methodology applied in this paper allowed to introduce in the model wind effects in a satisfactory manner. The drop size distribution parameters identified from field experiments and model runs were D_{50} = 1.30 mm and n = 2.50. A relationship was found between the corrector parameters (K_1 and K_2) and the wind speed. For wind speed below 1.1 m s^{-1}, correction of the aerodynamic drag coefficient C was not required. The variation of K_1 with the wind speed was linear, while a step function was used to model the effect of wind speed on K_2.

After calibration, Ador-Sprinkler adequately predicted the spatial irrigation water distribution during the whole corn development season. Although partial and complete irrigations were simulated, the best results were obtained for complete irrigation events. The average *RMSE* between measured and simulated water application (0.95 mm h^{-1}) was comparable to the average *RMSE* between the measured water distributions in plots A and B (0.63 mm h^{-1}). Therefore, a relevant part of the simulation error could be attributed to experimental errors.

The Ador-Crop model was compared with CropWat. Both models produced similar yield reductions (R^2 = 0.988***). The best fit was obtained when a linear distribution at the end of the months was used in CropWat to extrapolate monthly ET_0. The plot of measured and Ador-Crop simulated yield reduction *vs.* soil available water resulted in similar features, but the scatter was much larger for the measured yield reduction than for the simulation results, indicating that in the real world factors other than water availability affect crop yield.

AdorSim was validated comparing the measured and simulated values of *YR*. The coupled model explained 25 %** of the variability in measured *YR*. Although this percentage may seem modest, it is similar to previous findings in similar approaches used in surface irrigation. Most of the unexplained variability is due to the effect of non water-related factors affecting crop yield.

The fact that the coupled model uses thermal time to simulate crop growth makes it very adequate to assess irrigation performance using time series, in which historical meteorological data could be used to analyze crop response to different irrigation strategies. AdorSim could be an adequate tool to: 1) Assess the effect of changes in the solid-set design on irrigation performance and crop yield; 2) Analyze the current irrigation practices in windy areas where solid set sprinkler irrigation is relevant; 3) Characterize the relationship between wind speed and direction and irrigation uniformity and crop yield; and 4) Investigate irrigation scheduling scenarios based on the meteorological factors affecting irrigation water distribution, and soil, water, and irrigation system constraints. In Chapter 5, AdorSim will be applied to address some of these questions in the context of a corn crop in the middle Ebro valley in NE of Spain.

RESUMEN Y CONCLUSIONES

La simulación del riego por aspersión en cobertura total bajo condiciones de viento es una tarea complicada, debido a la frecuente variación de la velocidad y dirección del viento durante un riego. La metodología aplicada a la calibración del modelo en este artículo permitió introducir en el modelo los efectos del viento de forma satisfactoria. Los parámetros de distribución de los tamaños de gota identificados a partir de experimentos de campo y ejecuciones del modelo fueron D_{50} = 1,30 mm, y n = 2,50. Se describió una relación entre los parámetros correctores del coeficiente aerodinámico (K_1 y K_2) y la velocidad del viento. Para velocidades de viento inferiores a 1,1 m s^{-1}, la corrección del coeficiente aerodinámico no fue necesaria. La variación del coeficiente K_1 con el viento resultó ser lineal, mientras que para expresar la variación de K_2 se empleó una función discontinua por tramos.

Una vez completada la fase de calibración, el modelo Ador-Sprinlkler predijo adecuadamente la distribución del agua de riego durante todo el ciclo del cultivo. Aunque se simularon riegos parciales y completos, los mejores resultados de obtuvieron para los riegos completos. El valor medio del *RMSE* entre la aplicación de agua medida y simulada (0,95 mm h^{-1}) resultó ser comparable al *RMSE* medio entre las distribuciones medidas del agua de riego en los marcos A y B (0,63 mm h^{-1}). Por lo tanto, una buena parte del error en la simulación pudo ser atribuida a errores experimentales.

El modelo Ador-Crop se comparó con el modelo CropWat. Ambos produjeron resultados similares de reducción del rendimiento (R^2 = 0,988***). El mejor ajuste entre ambos modelos se obtuvo cuando en CropWat se usó una distribución lineal en el extremo de los meses para extrapolar los valores mensuales de la evapotranspiración de referencia. El gráfico que presenta los valores de la reducción del rendimiento medida y simulada frente al agua estacional disponible para el cultivo frente a reducción de cultivo mostró los mismos rasgos. En el caso de los valores medidos la dispersión fue muy superior a la de los valores simulados, indicando que en el mundo real otros factores además del estrés hídrico afectan a la producción de los cultivos.

AdorSim se validó comparando los valores medidos y simulados de *YR*. El modelo combinado explicó el 25 %** de la variabilidad en la medida de *YR*. Aunque este porcentaje pueda parecer modesto, es similar al encontrado en trabajos previos en riego por superficie. La mayoría de la variabilidad no explicada por el modelo es debida al efecto sobre la producción del cultivo de factores no relacionados con el agua.

El hecho de que le modelo combinado use tiempo térmico para simular el crecimiento de los cultivos lo hace muy indicado para evaluar la calidad del riego utilizando series temporales, en las que los datos meteorológicos históricos se podrían utilizar para analizar la respuesta del cultivo a distintas estrategias de riego. AdorSim podría ser una herramienta adecuada para: 1) Evaluar el efecto del cambio de algunos parámetros de diseño de la cobertura sobre el uso del agua y el rendimiento de los cultivos; 2) Analizar las prácticas de riego actuales en zonas de fuertes vientos y en las que abunda el riego por aspersión en cobertura total; 3) Caracterizar las relación entre la velocidad y dirección del viento, la uniformidad del riego y la pérdida de rendimiento de los cultivos; y

4) Investigar escenarios de programación del riego basados en los factores meteorológicos que afectan a la distribución del agua de riego y a las restricciones impuestas por los factores de suelo, agua, y sistemas de riego. En el capítulo 5, AdorSim se aplicará de forma exploratoria a resolver alguna de estas cuestiones en el contexto del cultivo del maíz en el valle medio del Ebro.

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NOTATION

The following symbols are used in this paper:

A = acceleration of the drop in the air (m s^{-2});
a_d, a_n = empirical coefficients;
AWD = allowable water depletion limit (mm);
b_d, b_n = empirical coefficients;
C = drag coefficient;
CU = Christiansen's uniformity coefficient (%);
CU_{abs} = absolute difference between the measured and simulated CU (%);
d = roughness height (m);
D_{50} = volume mean drop diameter (mm);
D = drop diameter (m);
Dp = deep percolation (mm);
D_r = root zone depletion (mm);
ETa = actual crop evapotranspiration (mm);
ETc = crop evapotranspiration (mm);
ET_0 = reference evapotranspiration (mm);
ET_{max} = maximum crop evapotranspiration (mm);
f = number of development stages;
Fr = resistance force (NW);
GY = grain yield (kg ha^{-1});
ID = irrigation depth (mm);
$\overline{ID}$ = average irrigation depth (mm);
IDc = catch can irrigation depth (mm);
$IDcs$ = Seasonal irrigation depth (mm);
IE = irrigation evaluation;
IEp = partial irrigation evaluation;
K_1, K_2 = empirical parameters;
K_c = crop coefficients;
K_y = crop yield sensitivity to water deficits;
m = drop mass (kg);
n = dimensionless exponent;
n_c = number of catch cans;
P = precipitation (mm);
P = depletion factor (%);
P_v = percent of total discharge in drops smaller than D (%);
PAE_{lq} = potential application efficiency of the low quarter (%);
$RMSE$ = Root Mean Square Error;
r = coefficient of correlation;
R = ratio of nozzle size to pressure head;
S = standard deviation;
SAW = seasonal available water (mm);
SWC = soil water content (mm);
SWD = soil water depletion (mm);
t = time (s);
TAW = total available water (mm);

U = drop velocity with respect to the ground (m s^{-1});
UD = uniformity of distribution (%);
V = velocity of the drop in the air (m s^{-1});
W = wind velocity vector;
$WDEL$ = wind drift and evaporation losses (%);
x, y, z = Cartesian coordinates referring to the ground (m);
Y_a = actual yield (kg ha^{-1});
Y_{max} = maximum yield (kg ha^{-1});
YR = yield reduction (%);
z_0 = roughness parameter (m);
α = angle formed by vectors V and W;
β = angle formed by the vectors V and U;
ρ_a = density of the air (g m^{-3});
ρ_W = density of the water (g m^{-3});

Subscripts
a = at reference height a;
i = square or catch can *i*;
j = day j;
m = measured;
s = simulated;
z = at height *z*.

CHAPTER V

A COUPLED CROP AND SOLID-SET SPRINKLER SIMULATION MODEL: II. MODEL APPLICATION

RESUMEN

En este capítulo se presentan varias aplicaciones del modelo combinado de simulación de riego en cobertura total y de cultivos AdorSim. El modelo se basa en la teoría balística para la simulación del riego por aspersión, e incluye un modelo de cultivos basado en CropWat. El desarrollo del modelo, así como su calibración y validación se presentaron en el Capítulo 4. El experimento presentado en el Capítulo 3 sobre un cultivo de maíz se usó para estos propósitos. El uso del modelo se enfrenta a una serie de limitaciones que limitan su aplicabilidad. Entre ellas se incluye la necesidad de continuar con el desarrollo del modelo, así como la falta de datos meteorológicos detallados en las zonas de riego con cobertura total. A pesar de estas limitaciones, el modelo se aplico par estudiar diversos problemas de diseño y manejo del riego por aspersión. Los resultados más relevantes fueron los que se obtuvieron de la caracterización de técnicas avanzadas de programación de riegos. Las diferencias en el rendimiento del cultivo y el uso del agua derivadas de regar a diferentes horas del día se estimaron en dos localidades con importantes diferencias en su exposición al viento. En estas localidades se desarrollaron curvas para relacionar el agua usada con el descenso del rendimiento de los cultivos. La simulación se aplicó también a la estimación de valores umbrales de viento para un manejo óptimo del riego. En la localidad más expuesta al viento el umbral de 2,5 m s^{-1} resultó adecuado para controlar la caída del rendimiento y para minimizar el uso del agua.

ABSTRACT

In this Chapter, applications of the coupled solid-set sprinkler irrigation and crop model AdorSim are presented. The model is based on ballistic theory for sprinkler irrigation simulation and includes a CropWat based crop model. In Chapter 4 the model development, calibration and validation was presented. The experiment reported in Chapter 3 on a corn crop was used for these purposes. Model application faces a number of circumstances limiting its applicability, including the need for further model development and the availability of detailed meteorological information about solid-set irrigated areas. Despite these limitations, the model was exploratorily applied to a number of design and management issues in solid-set irrigation. The most relevant results are related to the characterization of advanced irrigation scheduling strategies. The differences in crop yield and water use derived from conducting irrigations at different times of the day were estimated for two locations strongly differing in wind speed. Irrigation guidelines were established in these locations to relate gross water use and water stress induced yield reductions. Simulations were also applied to estimate the value of wind speed thresholds for irrigation operation. In the windy location, a threshold of 2.5 m s^{-1} resulted adequate to control yield reductions and to minimize water use.

INTRODUCTION

In arid and semi-arid areas, agricultural production depends upon effective irrigation. In a context of increasing water costs, developing adequate irrigation scheduling requires knowledge of soil water properties, crop water requirements, meteorology, and yield response to irrigation water. In sprinkler irrigation (as opposed to surface irrigation) irrigation scheduling can be effectively used by farmers, since the irrigation depth can be easily adjusted and pressurized distribution systems are often operated with a high degree of flexibility. A number of techniques can be applied to establish optimum management strategies leading to a minimization of water inputs, the control of potentially unfavorable meteorological conditions and the optimization of crop yields. These techniques can be used to improve the design and/or the management of on-farm irrigation equipment.

In the middle Ebro valley of northeastern Spain, wind is the major environmental factor affecting sprinkler irrigation performance. In this area, sprinkler irrigation management is primarily determined by the wind. Farmers concentrate irrigation operations in calm days in order to conserve water and maintain an acceptable level of uniformity. When windy conditions prevail, farmers are forced to irrigate under moderate and high wind conditions, therefore accepting poor irrigation performance and reduced yields.

In the last decades, several studies have been performed to identify design and management problems of irrigated areas equipped with modern sprinkler irrigation systems in the Ebro Basin (Dechmi et al., 1998; Dechmi et al., 1999; Dechmi et al., 2000; Faci, 1988; Faci and Bercero, 1991; Tejero, 1999). The purpose of these studies was to improve irrigation performance in the area. In Chapter 4, the computer model AdorSim has been presented. The model constitutes a decision support tool in sprinkler-irrigated agriculture. AdorSim consists on the combination of a ballistic sprinkler irrigation simulation model (Ador-Sprinkler) and a crop model (Ador-Crop). The irrigation routine is based on similar models in the literature (Carrión et al., 2001; Fukui et al., 1980; Montero et al., 2001; Seginer et al., 1991), and incorporates a drop size distribution curve (Kincaid et al., 1996), along with a locally calibrated predictive equation for wind drift and evaporation losses. The most innovative aspect of the model is that crop growth simulation is performed at a number of points within a sprinkler spacing, with a typical number of 25. Therefore, the spatial distribution of irrigation water is converted to a spatial distribution of crop yield reduction, and the effects of irrigation uniformity on crop yield can be properly assessed. Model validation was performed on a corn crop (*Zea mays* L.). The experimental solid-set was designed to represent a typical setup of the new irrigation developments in the Ebro basin. In the companion paper, the model was validated reproducing the experimental irrigation dates and times.

The objectives of this paper include: 1) Determine the effect of the sprinkler spacing and the azimuth of the sprinkler lines on irrigation performance and crop yield in the conditions of the validation experiment; and 2) Evaluate different wind-related irrigation scheduling strategies on irrigation performance and crop yield. In this second objective, the effect of water availability and irrigation time (closely related to the wind speed in the Ebro valley), the establishment of wind thresholds, and the variability of meteorological conditions among locations and irrigation seasons, will be explored.

EFFECT OF DESIGN PARAMETERS ON IRRIGATION PERFORMANCE AND CROP YIELD

Two design parameters were selected for this study: the sprinkler spacing and the azimuth of the sprinkler lines. Both parameters have been identified in this thesis as relevant to irrigation uniformity and crop yield (Chapters 1 and 2). In this simulation study, AdorSim will be applied in the validation conditions. The experimental irrigation dates, and amounts will be reproduced, and changes will only be introduced in the analysed variables.

Sprinkler spacing

Simulations were performed to analyse the effect of sprinkler spacing on irrigation uniformity, crop yield and deep percolation losses. AdorSim was run to simulate the following triangular (T) and rectangular (R) sprinkler spacings: 15 x 12 m, 15 x 15 m, 15 x 18 m, and 18 x 18 m. The only required adjustment on the input data was the duration of the irrigation events, which was corrected in each spacing to maintain constant the gross irrigation depth per irrigation event. From the results presented in Table V.1, the negative effect of wind speed on crop yield was alleviated by the use of narrow, triangular sprinkler spacings. In the experimental conditions, the differences between spacings attained a relevant 10.5 % of crop yield. In each sprinkler spacing (except for 18x18) the model detected an improvement in crop yield for triangular layouts. The variation of deep percolation losses among sprinkler spacings was not very relevant, although narrow spacings result in smaller water losses. The most relevant differences are in the average value of the Christiansen coefficient of uniformity ($\overline{CU}$), which varies from 63.9 to 83.5 %. These differences in uniformity seem to be the main cause of the differences in crop yield.

Table V.1. *Yield reduction [YR], average deep percolation losses [Dp], and average Christiansen coefficient of uniformity [*$\overline{CU}$*] obtained within four sprinkler spacings arranged in triangular and rectangular layouts.*

Tabla V.1. *Reducción del rendimiento [YR], pérdidas medias por percolación profunda [Dp], y promedio del coeficiente de uniformidad de Christiansen [*$\overline{CU}$*] obtenidos con cuatro marcos de aspersión en disposiciones triangular y rectangular.*

Sprinkler spacing	YR (%)	Dp (%)	$\overline{CU}$ (%)
T12x15	17.2	3.3	83.5
R12x15	18.9	3.3	81.8
T15x15	17.6	3.2	83.7
R15x15	18.3	3.4	80.3
T18x15	20.4	3.5	79.7
R18x15	24.5	4.8	71.2
T18x18	27.8	5.6	65.5
R18x18	27.7	5.8	63.9

Azimuth of the sprinkler line

According to Keller and Bliesner (1990), one of the design-time defenses against the negative effect of wind on solid-set sprinkler irrigation performance is the alignment of the sprinkler lines with respect to the dominant wind direction. In Chapter 1, the application of this criterion was evaluated in the Loma de Quinto District, in which triangular sprinkler layouts prevail. In this Chapter, two simulation experiments are presented, exploring the effect of sprinkler line alignment on irrigation performance and crop yield. In the first experiment, the solid-set field experiment (with a spacing of T18x15) was simulated with sprinkler line azimuths ranging between 0 and 60º (in triangular layouts two azimuths differing in multiples of 60º produce the same results). In the second experiment, the same simulation was performed using a R18x18 spacing, adjusting the irrigation time to maintain the same seasonal gross irrigation depth. Sprinkler line azimuths were simulated from 0 to 90º (in rectangular layouts two azimuths differing in multiples of 90º produce the same results). Simulation results for both experiments are presented in Table V.2.

Table V.2. *Yield reduction [YR], average deep percolation losses [Dp], and average Christiansen coefficient of uniformity [$\overline{CU}$] resulting from simulations with different sprinkler spacings and sprinkler line azimuths.*

Tabla V.2. *Reducción del rendimiento [YR], pérdidas medias por percolación profunda [Dp], y promedio del coeficiente de uniformidad de Christiansen [$\overline{CU}$] obtenidos en la simulación de diferentes marcos de aspersión y acimuts de la línea de aspersores.*

Sprinkler spacing	Sprinkler Line Azimuth (°)	YR (%)	Dp (%)	$\overline{CU}$ (%)
T 18 x 15	0	20.1	3.4	79.8
	10	20.0	3.4	79.9
	20	20.1	3.5	79.8
	30	20.3	3.6	79.8
	40	20.5	3.6	79.5
	50	20.6	3.7	79.5
	60	20.3	3.6	79.8
R 18 x 18	0	28.3	6.2	64.0
	15	27.9	5.8	63.9
	30	27.7	5.9	63.8
	45	28.0	6.2	64.0
	60	27.8	6.3	63.7
	75	27.8	6.3	63.7
	90	28.0	6.1	64.0

The azimuth of the sprinkler lines had not a relevant effect on the simulation results for both simulated spacing. The differences between simulated yield reductions among the various combinations of sprinkler spacing and line azimuth were only 0.6 %. The reasons for this limited effect can be found in the natural variability in wind speed and direction throughout the season (see Chapter 4 for details), and/or in limitations in the model predictive capability. Additional research is required to obtain solid conclusions on this issue.

CLIMATIC CHARACTERISTICS OF ZARAGOZA AND TAMARITE

The meteorological data used in this work for model input (wind speed and direction, global solar radiation, and air temperature and relative humidity) were recorded in two automated meteorological stations (Campbell Scientific, Logan, Utah) installed on grass in Zaragoza (41º 43´N, 0º49´W, 225 m of altitude) and Tamarite (41º 46´N, 0º 22´E, 218 m of altitude), north-eastern Spain and central Aragón Department (Figure V.1). Reference evapotranspiration (ET_0) was estimated using that meteorological data with the FAO version of the Penman-Monteith equation (Allen et al., 1998).

Figure V.1. *Localisation of the Zaragoza and Tamarite meteorological stations within Spain, the Ebro Basin and the Aragón Department.*

Figura V.1. *Localización de las estaciones meteorológicas de Zaragoza y Tamarite en España, el valle del Ebro y Aragón.*

The Zaragoza station will constitute the primary source of meteorological data for the model. The Tamarite station will be used as a contrast in the irrigation scheduling section. In both locations the climate is Mediterranean semiarid. In Zaragoza, the mean annual maximum and minimum daily air temperatures for the period 1995-2002 were 21.4ºC and 8.3 ºC, respectively, while the annual average precipitation and ET_0 were 353 mm and 1,197 mm, respectively. In Tamarite, the mean annual maximum and minimum daily air temperatures for the period 1997-2002 were 20.8 ºC and 7.0 ºC, respectively, while the annual average precipitation and ET_0 were 375 mm and 1,003 mm, respectively.

Zaragoza and Tamarite were considered in this study because of the relevant differences in the wind speed recorded at both locations, and because of the availability of adequate 30 min wind speed and direction data series (from 1996 to 2002 – seven years – in Zaragoza and from 1998 to 2002 – five years – in Tamarite). Zaragoza climate is characterized by the presence of an intense wind from the NW-W, locally called "*cierzo*". In Tamarite, *cierzo* is less intense than in Zaragoza. Figure V.2 presents the monthly average wind speed for the average year at the Zaragoza and Tamarite meteorological stations. In Tamarite the maximum monthly average wind speed was 1.5 m s^{-1}, while in Zaragoza monthly average wind speeds ranged from 1.9 m s^{-1} to 3.0 m s^{-1}.

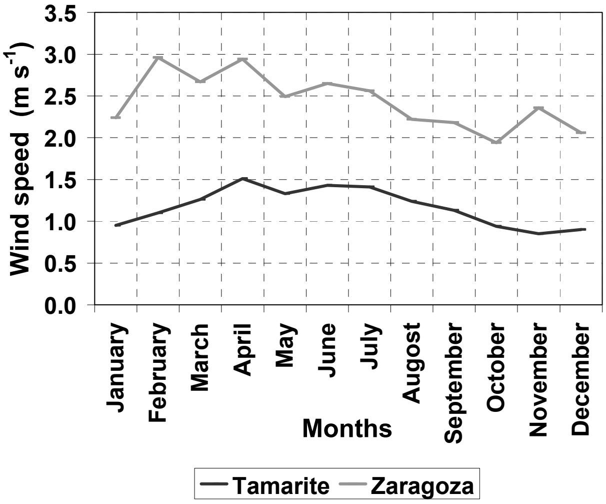


Figure V.2. *Monthly average wind speed for the average year at the Zaragoza and Tamarite meteorological stations.*

Figura V.2. *Velocidad de viento media mensual para el año medio en Zaragoza y Tamarite.*

Table V.3 presents the inter-annual variation of annual average wind speed (*W*), maximum seasonal corn (*Zea mays* L.) evapotranspiration (*ETm*) and seasonal net irrigation requirements (*NIR*) calculated for optimum, non-limiting conditions for each considered year in Zaragoza and Tamarite. Both *ETm* and *NIR* were computed using the Ador-crop module of the proposed model. In accordance with the above paragraph, the annual average wind speed in Zaragoza was approximately double than in Tamarite. The inter-annual wind speed variability was also larger in Zaragoza than in Tamarite, being thewith respective *CV*'s of 9.8 % and 3.8 %. Yearly corn *ETm* and *NIR* were larger in Zaragoza than Tamarite. The inter-annual differences were 60 and 57 mm for *ETm* and *NIR,* respectively.

Table V.3. *Inter-annual variation of the annual average wind speed [W], seasonal maximum corn evapotranspiration [ETm] and seasonal corn net irrigation requirements [NIR] in the Zaragoza and Tamarite meteorological stations.*

Tabla V.3. *Variación interanual de la velocidad de viento media anual [W], de la evapotranspiración estacional máxima del maíz [ETm] y de las necesidades netas de riego estacional del maíz [NIR] en las estaciones meteorológicas de Zaragoza y Tamarite.*

Years	Zaragoza			Tamarite			Difference	
	W ($m\ s^{-1}$)	ETm (mm)	NIR (mm)	W ($m\ s^{-1}$)	ETm (mm)	NIR (mm)	ETm (mm)	NIR (mm)
1996	2.3	643	561	-	-	-	-	-
1997	2.1	587	434	-	-	-	-	-
1998	2.7	681	568	1.2	605	517	76	51
1999	2.7	585	488	1.2	567	441	19	47
2000	2.3	702	652	1.2	613	522	89	130
2001	2.2	658	590	1.1	573	480	85	110
2002	2.4	686	530	1.2	589	486	96	44
Average	2.4	649	546	1.2	589	489	60	57

A detailed characterization of the hourly, daily and monthly and wind speed in Zaragoza is presented in the following paragraphs. The purpose of this section is to provide insight on the nature of wind in the primary location of meteorological data.

Daily evolution of wind speed in Zaragoza

Figure V.3 presents the daily evolution of 30 min (GMT) monthly average wind speed in Zaragoza. The figure separates the monthly curves by seasons, since similar traits can be observed within each season in the daily *W* pattern. This similitude consists on the daytime range during witch *W* exceeds 2 m s^{-1}, and the time of the maximum average wind speed. This value was higher than 3.5 m s^{-1} only for tree months (February, March and

April). In the case of February the average wind speed was higher than 2 m s^{-1} during the whole day.

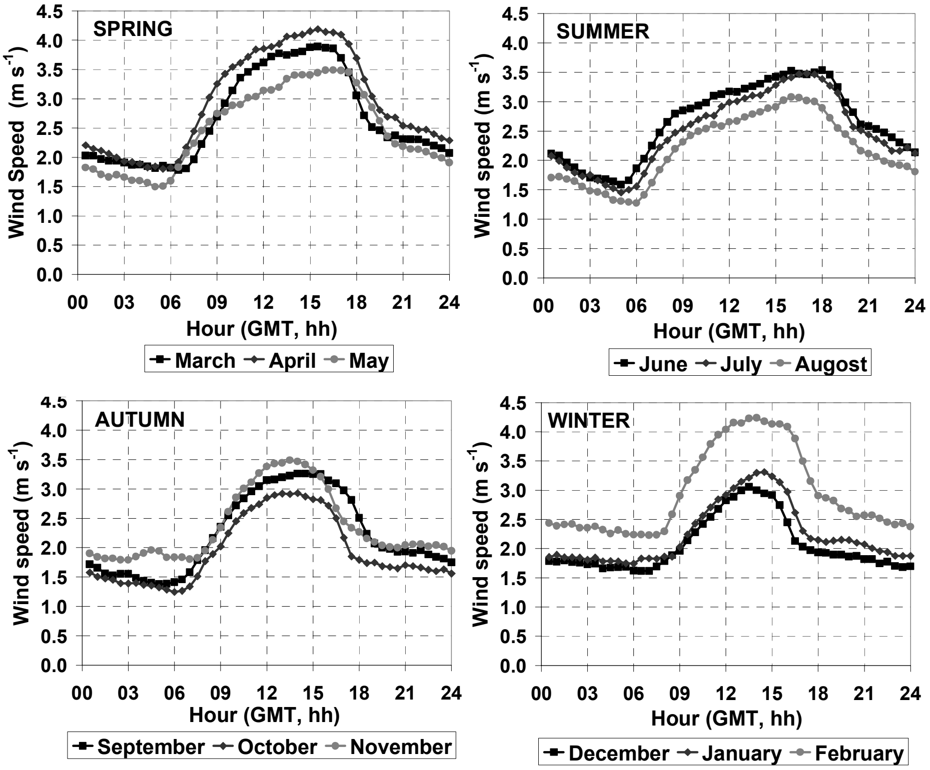


Figure V.3. *Semi-hour monthly average wind speed recorded in the Zaragoza meteorological station along the day (from 0 h to 24 h GMT).*

Figura V.3. *Velocidad del viento media semi-horaria medida en la estación meteorológica de Zaragoza a lo largo del día (de 0 h a 24 h GMT).*

Monthly wind pattern in Zaragoza: day and night wind speeds

In springtime the average wind speed was less than 2 m s^{-1} between the time interval of 0 h and 6 h GMT. During the summertime, this range extends from 0 h to 8 h GMT and during September, this range attained a maximum span: from 20 h to 6 h GMT of the following day. During those time ranges, the percentage of winds higher than 2 m s^{-1} was between 21 % and 38 % during spring, between 19 and 43 % during the summertime and between 19 % and 30 % during September (Figure V.4). Irrigation during the selected periods would be very effective to minimize wind drift and evaporation losses, maximize irrigation uniformity and efficiency and optimise crop yield. However, an irrigation system cannot be designed to operate between 6 and 10 hours a day, since the resulting costs would not be acceptable for most crops.

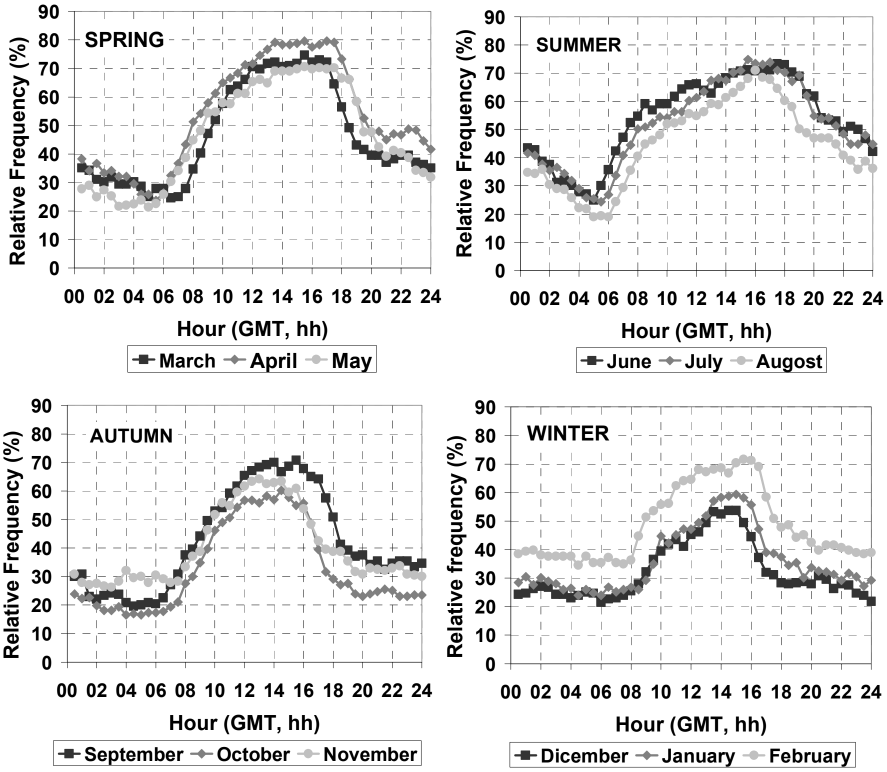


Figure V.4. *Semi hour monthly average relative frequency of Wind speeds higher than 2.0 m* s^{-1}*, recorded in the Zaragoza meteorological station.*

Figura V.4. *Frecuencia relativa de las medias mensuales de las velocidades de viento semi-horarias superiores a 2.0 m* s^{-1}*, medidas en la estación meteorológica de Zaragoza.*

GENERAL IRRIGATION SCHEDULING SIMULATION CRITERIA

In the upcoming sections the irrigation scheduling routine of AdorSim will be applied. Irrigations will be performed in different days, at different hours and for different durations. In the following paragraphs, the general irrigation criteria are presented.

All meteorological data were recorded in GMT time. The daytime period was considered from 4h to 20h GMT. The distinction between daytime and nighttime in the model implies the use of different equations for wind drift and evaporation loses (*WDEL*). During the daytime, the predictive equation developed in Chapter 3 was used:

$$WDEL = 5.287W + 7.479 \qquad [1]$$

During the nighttime, the intercept of the equation was used, following the findings of Salvador (personal communication, 2002), who found experimental evidence supporting that during the nighttime the *WDEL* of solid-set sprinkler irrigation were statistically independent of wind speed and other meteorological variables, and that nighttime *WDEL* were similar to the intercept of the daytime equation.

In AdorSim, an irrigation event is demanded when a critical percentage of the solid-set area is water stressed. This critical stress parameter is an additional model variable, acting as an index of deficit irrigation. Merriam and Keller (1978) proposed irrigation adequacy criteria based on the low quarter distribution. Following this concept, an irrigation is performed when the soil available water has been depleted in 25 % of the field area. If the soil water follows a normal distribution, this means that at this time 12.5 % of the field area will already be water stressed. Therefore, the adequacy criterion corresponds to a critical stress of 12.5 % of the area. In AdorSim, simulations have been performed with the critical stress ranging from 4 % to 48 % (between 1 and 12 stressed subplots, out of the total number of 25). The particular irrigation scheduling parameters of each simulation determine the model reaction to an irrigation demand. When the irrigation is finally performed, AdorSim searches the meteorological database to identify the average meteorological conditions during the irrigation event. The model determines the weighted average wind direction corresponding to the class in witch the recorded wind direction during the irrigation event was most frequent (see Chapter 4).

The sprinkler irrigation system layout, and the corn (*Zea mays* L.) parameters determined during the field experiment reported in Chapter 3 were used in the following irrigation scheduling simulations.

EFFECT OF THE CRITICAL STRESS LEVEL

A preliminary simulation was performed to explore the effect of the critical stress level on irrigation performance and crop yield. The simulation involved on-demand 4 h irrigation events starting at 8 h GMT and ending at 12 h GMT, using the meteorological data for Zaragoza in 2000. The twelve above-mentioned levels of critical stress (from 4 to 48 %) were simulated (Table V.4).

Results indicate that yield reduction increases linearly with critical stress, from 0.86 % to 13.39 %. At the highest critical stress the number of irrigation events was reduced from 40 to 30 (compared to the lowest critical stress level). As expected, differences were not appreciable in the average *CU* or in the average wind speed during the irrigation events. This result indicates the weakness of irrigation uniformity alone for explaining water stress induced yield reductions.

Table V.4. *Number of irrigation events [#IE], Corn yield reduction [YR], average Christiansen Coefficient of Uniformity [$\overline{CU}$], seasonal water use [WU] and average wind speed during the irrigation events [W] for each value of critical stress. The irrigation duration was 4 hours, between 8 and 12 h GMT. The meteorological data correspond to Zaragoza 2000.*

Tabla V.4. *Número de riegos [#IE], Reducción del rendimiento del maíz [YR], Coeficiente de uniformidad de Christiansen medio [$\overline{CU}$], uso de agua estacional [WU] y velocidad de viento media durante los riegos [W] para cada valor del nivel de estrés crítico. La duración de los riegos fue de 4 horas, entre las 8 y las 12 h GMT. Los datos meteorológicos son los de Zaragoza en el año 2000.*

Critical stress(%)	#IE (-)	YR (%)	$\overline{CU}$ (%)	WU (mm)	$\overline{W}$ (m s^{-1})
4	40	0.86	67.94	1011	3.13
8	37	1.79	69.73	935	2.97
12	38	3.22	66.54	961	3.50
16	36	4.04	67.64	910	3.38
20	34	4.68	68.49	859	3.11
24	34	5.73	67.82	859	3.29
28	34	6.99	65.73	859	3.39
32	35	7.91	64.42	884	3.65
36	32	9.15	67.71	809	3.35
40	30	9.94	71.81	758	2.74
44	32	11.2	64.32	809	3.52
48	30	13.39	67.90	758	3.08

The comparison of the cumulative catch can irrigation depth resulting from this simulation experiment with the field experimental data presented in Chapter 3, for different values of critical stress is presented in Figure V.5. This comparison seems adequate since the irrigation events lasted four hours on the average and were applied in approximately the same morning hours. The experimental conditions are equivalent (in terms of cumulative catch can irrigation depth) to a critical stress value of 28 %. The corresponding yield reduction presented in Table V.4 is 7 %, while the AdorSim results for the irrigation scheduling in the experimental conditions (which consisted in applying the crop water requirements considering the average catch can irrigation depth applied during each irrigation) indicated that the resulting *YR* was 17 %. These results suggest that and additional 10 % yield could be obtained just by improving irrigation scheduling, considering the spatial variability of water distribution. A similar finding was presented in Chapter 2 for the Loma de Quinto District.

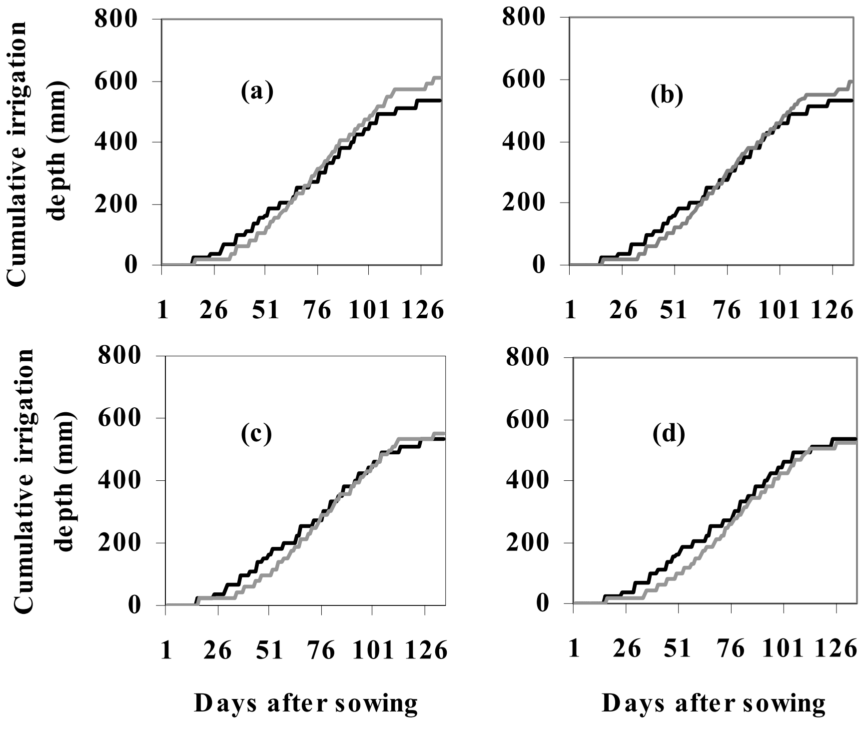


Figure V.5. *Time evolution of the Cumulative simulated (grey line) and experimental (black line) catch can irrigation depth for critical stress levels of 4 % (a), 12 % (b), 28 % (c) and 48 % (d).*

Figura V.5. *Evolución temporal de la dosis de riego en pluviómetros medida y simulada para niveles de estrés crítico del 4 % (a), 12 % (b), 28 % (c) y 48 % (d).*

ANALYSIS OF IRRIGATION SCHEDULING STRATEGIES

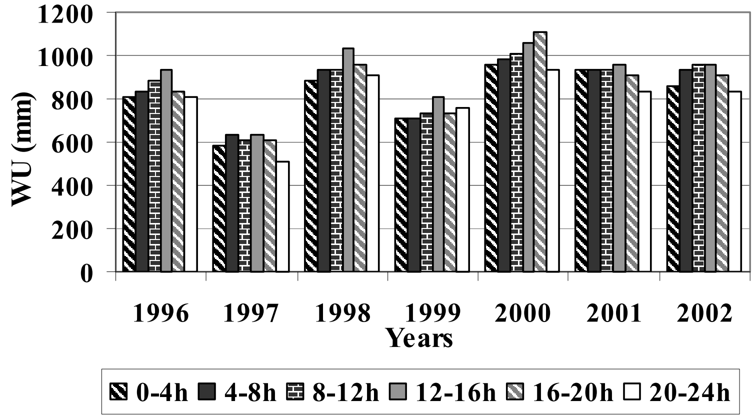
Two irrigation scheduling strategies were simulated to explore opportunities to conserve water and improve crop yield in solid-set sprinkler irrigated corn. The purpose was to establish the inter-annual effect of the variability in the meteorological parameters affecting sprinkler irrigation performance, corn yield reduction (*YR*), water use (*WU*) and deep percolation loses (*Dp*). The day was divided in 6 time periods of 4 hours starting at 0 h GMT. A total available water (*TAW)* of 170 mm m^{-1} and a soil depth of 0.9 m were considered. The soil water content was considered initially at field capacity.

Fixed time, rigid schedule irrigation

Under this scheduling option, an irrigation is performed the day after the critical stress level is attained, and all irrigations last for 4 h. Simulations were performed for each irrigation starting time, each year of the data set in Zaragoza and Tamarite, and the 12 levels of critical stress. For each year and irrigation time, the *YR*, *WU* and *Dp* resulting from the 12 critical stress levels were averaged and the CV was calculated.

A detailed case corresponding to a critical stress level of 4 % in Zaragoza and Tamarite is presented in Figures V.6 and V.7. Regarding seasonal *WU* in Zaragoza (Fig. V.6a.), results show a clear variability between years and between irrigation times. The difference between the daytime irrigation times (from 4 to 20 h GMT) was 129 mm on the average. This difference indicates the relevance of selecting a proper irrigation time. The minimum seasonal *WU* corresponds to the nighttime (time periods between 0 and 4h GMT and between 20 and 24h GMT). In most cases, the maximum *WU* was applied if irrigation was performed between 12 and 16 h GMT. The yearly average *WU* ranged from 594 to 1,011 mm. This high variability was not only due to inter-year variation in evapotranspiration (Table V.1). In fact, most of the *WU* variability was due to inter-year wind speed variability.

a)



b)

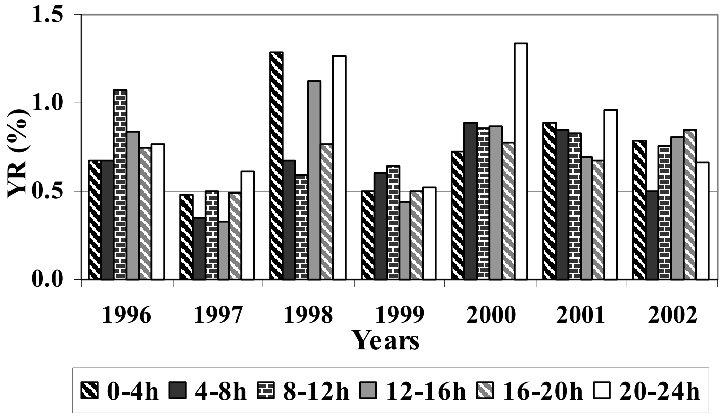


Figure V.6. *Water use [WU] (a); and yield reduction [YR] (b) for each year and each irrigation time considering a critical stress of 4 % and using Zaragoza meteorological data.*

Figura V.6. *Agua usada [WU] (a); y reducción del rendimiento [YR] (b) para cada año y cada horario de riego considerando un nivel de estrés crítico del 4 % y usando los datos meteorológicos de Zaragoza.*

The inter-year pattern of *YR* variability reproduces the variability in *WU* (Fig. V.6b). The variability between irrigation times does not follow any trend, and the values can be considered non relevant (between 0.33 % and 1.34 %), as a consequence of the low critical stress level.

Simulation results for Tamarite show much less inter-year and inter-time variability in *WU* than in Zaragoza (Fig. V.7a). Also, much less water was required (minimum *WU* of 531 mm and maximum *WU* of 758 mm). The difference between the daytime irrigation times was 61 mm on average. Concerning YR, the results were similar to those obtained for Zaragoza.

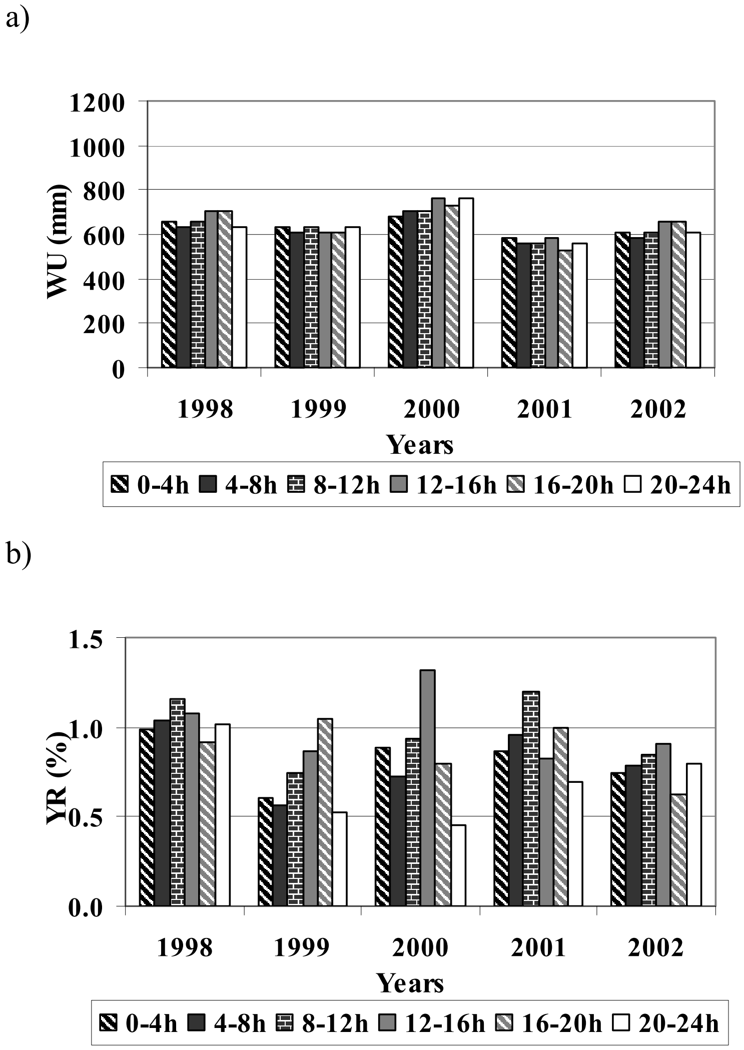


Figure V.7. *Water use [WU] (a); and yield reduction [YR] (b) for each year and each irrigation time considering a critical stress of 4% and using Tamarite meteorological data.*

Figura V.7. *Agua usada [WU] (a); reducción del rendimiento [YR] (b) para cada año y cada horario de riego considerando un nivel de estrés crítico del 4 % y usando los datos meteorológicos de Tamarite.*

Figure V.8 presents contour line maps of *YR*, *WU* and *Dp* in a domain of critical stress and irrigation time for Zaragoza and Tamarite. Both locations, present similar traits for *YR*. For the same irrigation time and critical stress, yield is more severely reduced in Zaragoza than in Tamarite. *YR* does not show a clear variation with the irrigation time, but increases linearly with the critical stress. As for *WU*, more water is required in both locations to obtain the same *YR* as the irrigation time approaches midday. In fact, *WU* shows the same daily pattern as the wind speed.

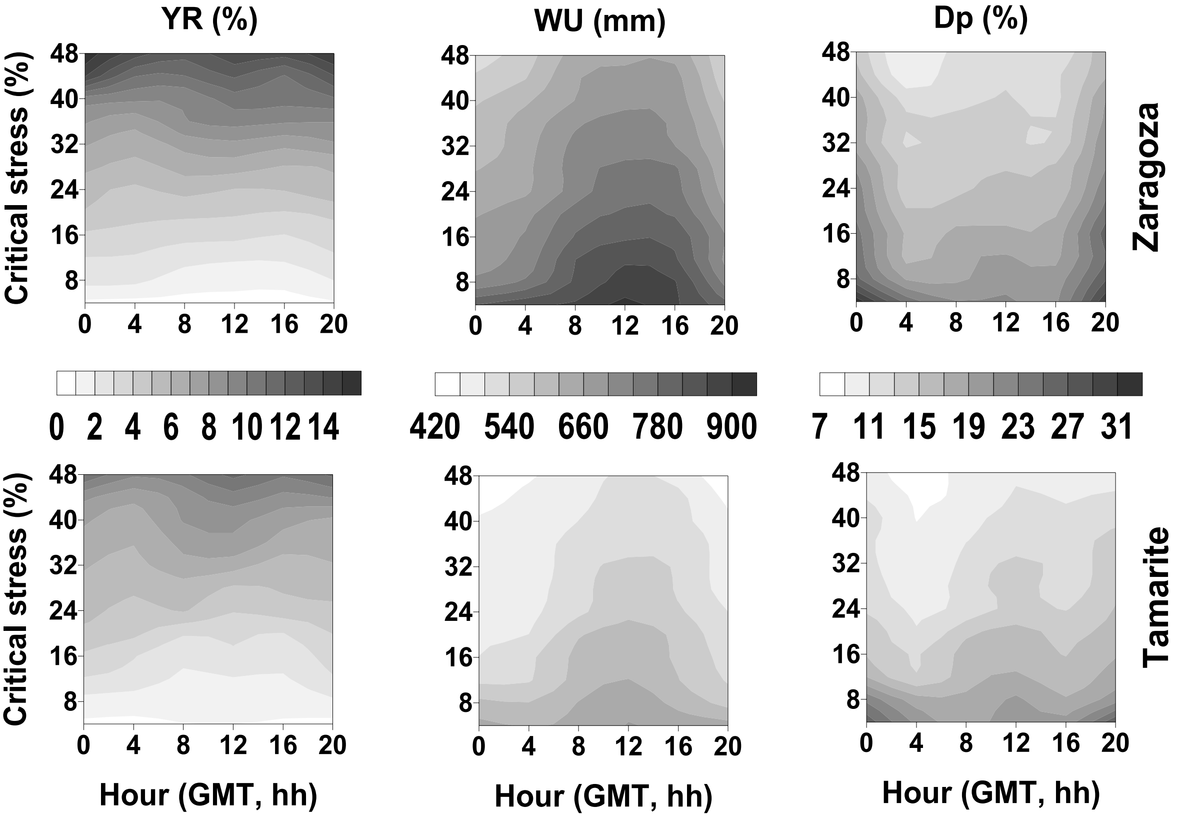


Figure V.8. *Contour line maps of yield reduction [YR], water use [WU] and deep percolation [Dp] losses resulting from combinations of irrigation time and critical stress. Results are presented for Zaragoza and Tamarite.*

Figura V.8. *Mapas de curves de nivel para la reducción del rendimiento [YR], el agua usada [WU] y las pérdidas por precolación profunda [Dp] derivadas de combinaciones del horario de riego y el nivel de estrés crítico. Los resultados se presentan para Zaragoza y Tamarite.*

Regarding deep percolation, losses were higher during the nighttime than during the daytime. This seems to be due to the fact that *WDEL* are smaller during the night. Consequently, during the night the catch can irrigation depth is larger and so are the chances of deep percolation losses. As previously observed, more water is required in Zaragoza to obtain the same yield as in Tamarite. Since the average difference in *ETm* between both locations is just 60 mm, and irrigation uniformity is lower in Zaragoza, the irrigation scheduling led to more frequent irrigation events, more irrigation water and higher deep percolation in Zaragoza.

Table V.5 presents the inter-year and inter-time average simulation results for Zaragoza and Tamarite. The inter-time average reproduces the case in which a farm is divided in irrigation sectors irrigated sequentially (each sector will be irrigated at the same time throughout the season). Average results and *CV*'s are presented for *YR*, *WU* and *Dp* for each critical stress level and location. The variability in *YR* and *WU* was larger in Zaragoza than in Tamarite, responding to the wind speed variability. In both locations, the *WU* variability was independent of the critical stress. This variation was double in Zaragoza than in Tamarite, due to the effect of wind speed. *Dp* losses are lower and more variable in Tamarite than in Zaragoza. In both locations, *Dp* decreases as the critical stress increases because of the reduction in irrigation events (data not presented).

Under the hypotheses of this irrigation scheduling strategy, farmers irrigate regardless of the wind speed and the irrigation time. In such a case, a direct relationship can be obtained between *WU* and *YR*, without an explicit consideration of the critical stress level. Such relationship is presented in figure V.9 for the conditions of Zaragoza and Tamarite. These equations can be used for irrigation design and planning, since each point in the curve is an average containing relevant variability associated to the irrigation time and the meteorological conditions, primarily *W* and *ETm*. One particular application of such a curve is the determination of the optimum yield respect to water cost.

Table V.5. *Yearly and time period average of yield reduction [YR], water use [WU] and deep percolation losses [Dp] for each critical stress in Zaragoza and Tamarite. Coefficients of variation are presented in parenthesis.*

Tabla V.5. *Media anual y de horario de riego de la reducción del rendimiento [YR], el agua usada [WU] y las pérdidas por precolación profunda [Dp] para cada nivel crítico de estrés hídrico en Zaragoza y Tamarite. Los coeficientes de variación se presentan en paréntesis.*

Critical	Zaragoza			Tamarite			Difference	
stress	YR (%)	WU (mm)	Dp (%)	YR (%)	WU (mm)	Dp (%)	YR (%)	WU (mm)
4	0.7 (24.8)	853 (16.6)	25.1 (8.1)	0.9 (14.0)	638 (9.6)	21.9 (19.8)	-0.1	215
8	1.8 (18.1)	792 (17.8)	21.6 (14.9)	1.5 (12.2)	602 (9.1)	19.1 (17.1)	0.3	190
12	2.6 (21.1)	766 (17.1)	20.3 (13.7)	2.3 (8.1)	567 (8.7)	16.3 (21.8)	0.2	199
16	3.4 (16.9)	748 (17.0)	19.8 (12.7)	3.0 (8.0)	552 (8.9)	15.2 (23.8)	0.4	196
20	4.3 (19.0)	722 (16.8)	18.5 (16.9)	3.7 (14.0)	541 (8.2)	14.4 (25.8)	0.6	182
24	5.2 (14.6)	698 (17.2)	17.3 (16.7)	4.7 (7.9)	519 (8.6)	12.7 (31.6)	0.5	179
28	6.1 (17.1)	686 (17.0)	16.6 (14.8)	5.3 (8.5)	511 (9.6)	12.4 (32.6)	0.8	175
32	7.3 (17.3)	663 (17.1)	15.4 (17.1)	6.0 (9.4)	505 (8.4)	12.0 (32.0)	1.3	159
36	8.7 (17.2)	657 (16.5)	15.3 (18.5)	6.8 (9.2)	499 (8.4)	11.6 (32.9)	1.8	158
40	10.0 (14.6)	632 (16.6)	14.4 (20.4)	7.4 (6.9)	490 (8.0)	11.0 (30.7)	2.6	142
44	12.0 (16.4)	613 (17.6)	13.2 (22.8)	8.5 (11.0)	480 (7.5)	10.4 (30.6)	3.5	133
48	14.0 (14.7)	594 (16.8)	12.5 (26.3)	10.5 (17.7)	465 (7.0)	9.6 (29.8)	3.5	129

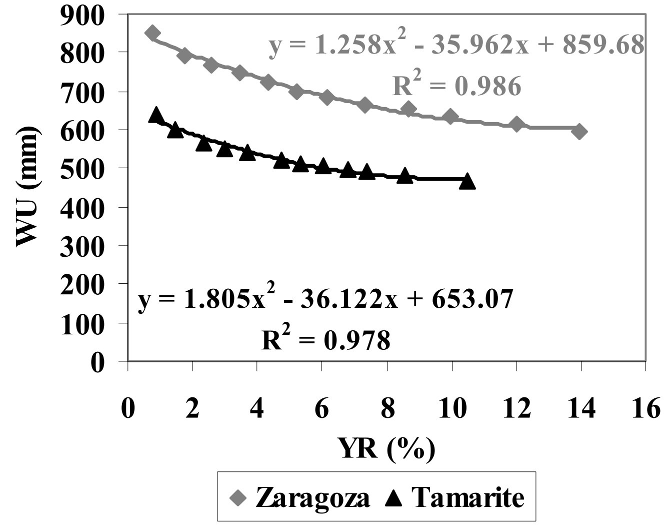


Figure V.9. *Irrigation system design and planning curve for Zaragoza and Tamarite. Water use [WU] is presented as a function of yield reduction [YR]. Black and gray lines correspond to regression lines between WU and YR in both locations.*

Figura V.9. *Curva de diseño y planificación del riego para Zaragoza y Tamarite. Se presenta el agua usada [WU] en función de la reducción del rendimiento [YR]. Las líneas negra y gris corresponden a regresiones entre WU y YR en ambas localidades.*

Fixed time, limited wind irrigation

In this irrigation scheduling strategy, an additional variable is introduced: the wind threshold. An irrigation is performed the first day after the critical stress level is attained and the wind speed is below the threshold at the selected irrigation time. If during the 4 h irrigation event the wind speed exceeds the threshold, irrigation is interrupted. Consequently, irrigation events have a maximum duration of 4 h. The magnitude of the threshold poses an additional threat to the crop: yield can also be reduced because of generalized water stress during a number of days with intense wind speeds and no irrigation.

Simulations were performed for the year 2000 in Zaragoza and Tamarite using wind speed thresholds varying from 1 to 7 m s^{-1} (with an increment of 0.5 m s^{-1}) for each irrigation time. Figure V.10 presents inter-time averages of *YR* and *WU* for a) Zaragoza, critical stress level of 4 %; b) Zaragoza, critical stress level of 24 %; and c) Tamarite, critical stress level of 4 %. Time averages are presented for the 24 h of the day and for a selective period between 20 h and 8 h of the following day. This is an extended nighttime period corresponding to the 12 h of low wind speeds.

Consideration of subfigures V.10 a and b indicates that the establishment of low wind thresholds results in deficit irrigation, with the consequent reductions in crop yield and water use. Moderate thresholds may lead to adequate combinations of *YR* and *WU*. If irrigation is performed 24 h a day, a threshold of 2.5 m s^{-1} in Zaragoza seems adequate to minimize *WU* and maintain moderate *YR* at both critical stress levels. Larger thresholds would not increase yield and would result in large *WU* and therefore *Dp* losses. If the solid-set capacity permits to select the best 12 h for irrigation operation (from 20 h to 8 h), the irrigation threshold can be slightly reduced to about 2 m s^{-1}.

Finally, the comparison of subfigures V.10 a and b permits to draw conclusions about the influence of the location on the wind threshold. Since wind is not such a relevant issue in Tamarite, the threshold is not so necessary as it is in Zaragoza. If irrigation is performed 24 h a day, a threshold of 2.0 m s^{-1} will be enough to grant almost full yield. If a 12 h nighttime operation is possible, the threshold is not required and irrigation can proceed regardless of wind speed without any damage to crop yield.

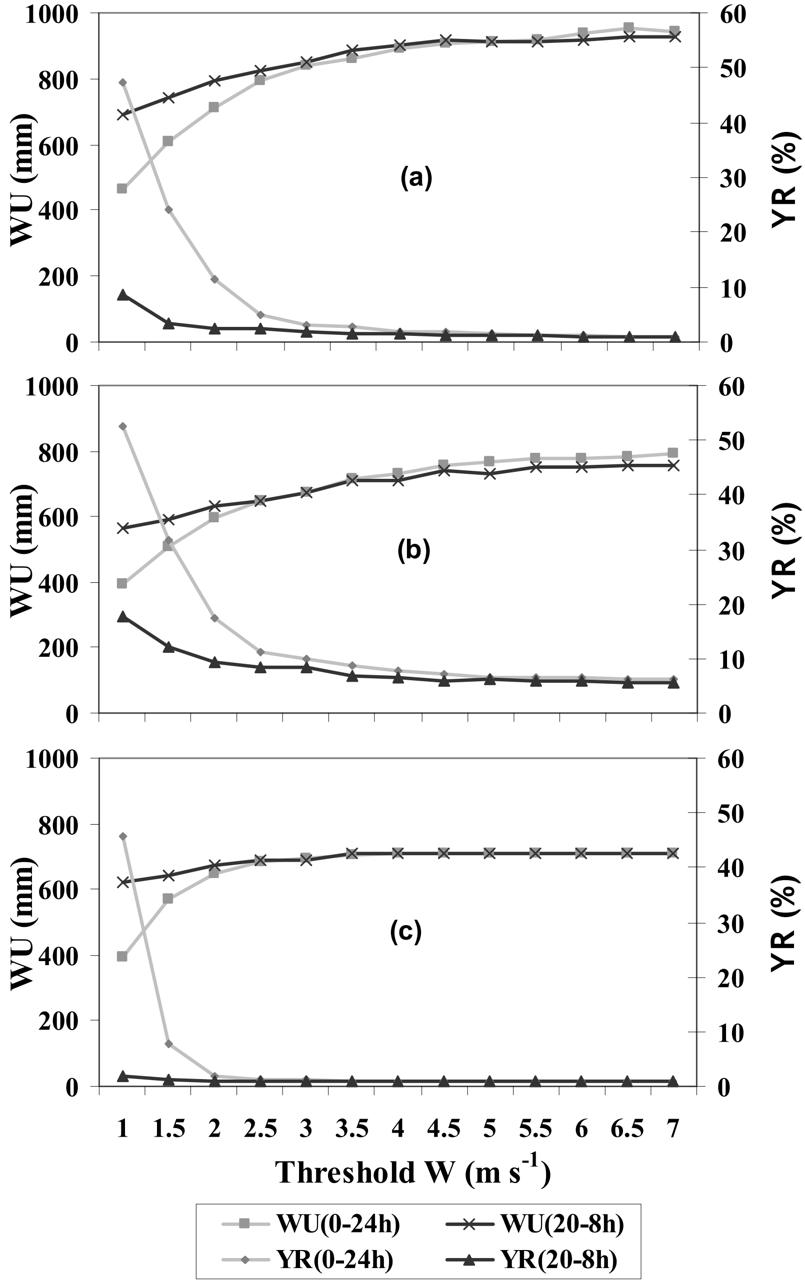


Figure V.10. *Limited wind irrigation schedule. Inter-time averages of yield reduction [YR] and water use [WU] for a) Zaragoza, critical stress level of 4 %; b) Zaragoza, critical stress level of 24 %; and c) Tamarite, critical stress level of 4 %. Time averages are presented for the 24 h of the day and for a selective period between 20 h and 8 h of the following day.*

Figura V.10. *Programación del riego con viento limitado. Promedios interhorarios de la reducción del rendimiento [YR] y el agua usada [WU] para a) Zaragoza, con un nivel de estrés crítico del 4 %; b) Zaragoza, con un nivel de estrés crítico del 24 %; y c) Tamarite, con un nivel de estrés crítico del 4 %. Se presentan los promedios interhorarios para las 24 h del día y para un periodo selectivo entre las 20 h y las 8 h del día siguiente.*

SUMMARY AND CONCLUSIONS

This chapter presents the application of the AdorSim simulation model to the analysis of several irrigation design and management issues. Although AdorSim was calibrated and validated in Chapter 4, all simulations presented in this chapter should be considered exploratory in nature.

In the experimental conditions, the effect of the sprinkler spacing is clear, and follows the expected trends. In this work we have been able to quantify the effect of the sprinkler spacing on crop yield. The sprinkler spacings currently used in the Ebro Valley resulted in corn yield differences of up to 10.5 %. The model predicted and average 1.6 % yield increase when a given spacing was switched from a rectangular to a triangular layout.

The most relevant conclusions are related to irrigation scheduling. When the model is run in automatic schedule mode, an irrigation is programmed when a given percentage of the solid-set spacing area is water stressed, according to the soil water balance performed in the crop simulation module. This percentage is referred to in the model as the critical stress level. Simulations were performed for critical stress between 4 and 48 %. As the critical stress progresses, the number of irrigation events decreases, the crop yield is reduced by water stress, and water use decreases. In a simulation experiment reproducing the field experiment reported in Chapter 3 the yield reduction ranged from 0.86 % to 13.39 %, while the water use decreased from 1011 to 758 mm.

Two irrigation scheduling strategies were explored and tested in two locations in the Ebro Valley of Spain: Zaragoza and Tamarite. The average wind speed for both locations was 2.4 and 1.2 m s^{-1}, respectively. In the first case of irrigation scheduling, an irrigation was performed the day after the critical stress condition was satisfied, regardless of the wind speed. All irrigation events in a given simulation were performed at the same time, and lasted for 4 h. Different simulations were performed scheduling irrigations at different times of the day, with a 4 h interval. Yield reductions were more relevant in Zaragoza (from 0.7 to 14.7 %) than in Tamarite (from 0.9 to 10.5 %). As for water use, much more water was required in Zaragoza (between 594 and 1011 mm) than in Tamarite (between 531 and 758 mm).

In the second irrigation scheduling strategy, an additional variable, the wind threshold, was introduced. If an irrigation is to be performed, AdorSim checks on the current wind speed and delays the irrigation event until the day in which the wind speed is lower than the threshold. This strategy has shown potential to limit yield reductions while minimizing water use. In the conditions of Zaragoza, a threshold of 2.5 m s^{-1} seems adequate, while in Tamarite the threshold can be reduced to 2.0 m s^{-1}. If the farmer can operate his solid-set exclusively between 20 h GMT and 8 h GMT (a 12 h night period), the threshold can be reduced to 2.0 m s^{-1} in Zaragoza and is not necessary in Tamarite.

Current developments in irrigation programmers and remote control of irrigation networks are offering new possibilities for advanced irrigation scheduling routines. The simulations presented in this Chapter should be further analysed to establish the bases for practical field applications improving water conservation and optimising crop yield.

RESUMEN Y CONCLUSIONES

En este Capítulo se presenta la aplicación del modelo AdorSim al análisis de varios problemas de diseño y de manejo del riego. Aunque AdorSim se calibró y validó en el Capítulo 4, todas las simulaciones presentadas en este capítulo tienen una naturaleza exploratoria.

En las condiciones experimentales, el efecto del marco de aspersión resulta claro, y sigue la tendencia establecida. En este trabajo se ha podido cuantificar el efecto del marco sobre el rendimiento del cultivo. Los marcos de aspersión que se usan actualmente en el valle del Ebro dieron lugar a diferencias en el rendimiento del maíz de hasta 10,5 %. El modelo predijo un aumento del rendimiento del 1,6 % en promedio cuando se cambia de un marco rectangular a uno triangular.

Las conclusiones más relevantes son las que guardan relación con la programación del riego. Cuando el modelo se ejecuta en modo de programación automática, se demanda un riego cuando un determinado porcentaje del marco de aspersión está estresado, de acuerdo con los resultados del balance de agua en el suelo que se desarrolla en el modelo de cultivos. Este porcentaje es el nivel de estrés crítico. Se realizaron simulaciones para valores del estrés crítico del 4 al 48 %. Conforme aumenta el estrés crítico, el número de riegos disminuye, el rendimiento se reduce por estrés hídrico, y el uso del agua disminuye. En un experimento de simulación que reprodujo el ensayo de campo del Capítulo 3, la reducción del rendimiento varió del 0,86 % al 13,39 %, mientras que el agua usada cayó de 1.011 a 758 mm.

Dos estrategias de programación de riegos se ensayaron y probaron en dos localidades del valle del Ebro (España): Zaragoza y Tamarite. El viento medio para ambas localidades fue de 2,4 y 1,2 m s^{-1}, respectivamente. En el primer caso de programación de riegos se aplicó el riego al día siguiente de que se cumpliera la condición de estrés crítico, sin prestar atención a la velocidad del viento. Todos los riegos de una determinada simulación se realizaron a la misma hora, y duraron 4 h. Las diferentes simulaciones programaron los riegos a diferentes horas del día, con intervalos de 4 h. Las reducciones del rendimiento fueron más importantes en Zaragoza (de 0,7 a 14,7 %) que en Tamarite (de 0,9 a 10,5 %). En cuanto al uso del agua, hizo falta mucha más agua en Zaragoza (entre 594 y 1,011 mm) que en Tamarite (entre 531 y 758 mm).

En la segunda estrategia de programación del riego se introdujo una variable adicional: el umbral de viento. AdorSim comprueba que la velocidad del viento esté por debajo del umbral antes de comenzar el riego. Si no es así, el riego se retrasa hasta el primer día en que el viento sea inferior al umbral. Esta estrategia se ha mostrado adecuada para limitar la caída del rendimiento al tiempo que se minimiza el uso del agua. En las condiciones de Zaragoza, un umbral de 2,5 m s^{-1} parece adecuado, mientras que en Tamarite el umbral puede ser reducido a 2,0 m s^{-1}. Si el agricultor puede regar su cobertura exclusivamente durante el periodo que va desde las 20 h GMT hasta las 8 h GMT del día siguiente (un periodo nocturno de 12 h), el umbral puede reducirse a 2,0 m s^{-1} en Zaragoza y deja de ser necesario en Tamarite.

Los desarrollos actuales en programadores del riego y sistemas de telecontrol de redes de riego ofrecen nuevas posibilidades para rutinas avanzadas de programación de riegos. Las simulaciones presentadas en este Capítulo deberían ser analizadas con más rigor para establecer las bases de aplicaciones prácticas que puedan mejorar la conservación del agua al tiempo que optimizan el rendimiento de los cultivos.

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CONCLUSIONES GENERALES

Del análisis detallado de los resultados y conclusiones obtenidas en los cinco capítulos que componen esta tesis, se pueden resaltar las siguientes conclusiones:

Al Objetivo 1 (Capítulos 1 y 2):

1. El elevado coste del agua de riego en relación con el margen bruto de los cultivos, las deficiencias técnicas de los sistemas de riego, y las limitaciones impuestas por el clima y los suelos en la comunidad de regantes de la Loma de Quinto (Zaragoza) son las causas principales de los problemas de uso del agua identificados.

2. Los amplios marcos de aspersión, las bajas presiones de funcionamiento y el uso de una única boquilla en los aspersores en las coberturas fijas de La Loma de Quinto, no aseguran una distribución adecuada del agua de riego. El marco de aspersión fue la variable que más afectó a la uniformidad de riego. Las evaluaciones de riego en coberturas indicaron que el Coeficiente de Uniformidad de Christiansen (*CU*) en la Loma es bajo (68,0 % en promedio). La validación de un modelo de simulación del riego para la predicción de *CU* permitió extender los resultados de las evaluaciones a todas las parcelas con cobertura total de la comunidad.

3. Las máquinas de desplazamiento lateral y los pivotes de la comunidad presentan mejor uniformidad que las coberturas totales. El promedio de *CU* fue de 80,0 % para las máquinas laterales y de 75,4 % para los pivotes.

4. En las coberturas totales el viento tuvo un gran efecto sobre la uniformidad de riego. Sin embargo, en las máquinas de riego, la uniformidad no resultó significativamente afectada por la velocidad del viento. De hecho, se obtuvieron uniformidades mayores con velocidades de viento de entre 2 y 6 m s^{-1} que en condiciones de calma.

5. Los suelos de la Loma de Quinto presentan limitaciones importantes para la práctica del riego por aspersión en las condiciones actuales. Un manejo adecuado del riego

precisaría de dosis pequeñas y riegos frecuentes, lo cual seria factible con la introducción de la automatización de los sistemas de riego.

6. El promedio del uso del agua en la comunidad fue de 477 mm en 1989, 995 mm en 1995 y 585 mm en 1997. Esta variabilidad en el uso del agua no pudo ser explicada ni por la aridez de cada año ni por los cambios en los cultivos. Los agricultores sometieron a sus cultivos a un estrés generalizado, que se caracterizó por un valor medio del índice estacional de calidad del riego (*IECR*) del 127 %.

7. De la simulación de una programación óptima del riego en parcelas de alfalfa de La Loma, se dedujo que los agricultores podrían conseguir un aumento de su margen bruto si aplicasen una cantidad adicional de riego del orden de 100 mm.

Al Objetivo 2 (Capitulo 3):

8. La velocidad del viento afectó de forma considerable al *CU* y a las pérdidas por evaporación y arrastre de un ensayo con un cultivo de maíz en una cobertura total de aspersión típica de las nuevas instalaciones del valle del Ebro. El 90 % de la variabilidad del *CU* fue estadísticamente explicado por la velocidad del viento. Este factor ambiental también explicó el 80 % de las pérdidas de agua por evaporación y arrastre. Estas pérdidas fueron muy relevantes en las condiciones experimentales (20 % del agua aplicada en promedio).

9. La uniformidad de la recarga del agua del suelo (60,5 %) fue menor que la uniformidad del riego (71,5 %), y la relación entre ambas variables fue estadísticamente significativa. En las condiciones experimentales el suelo no contribuyó a aliviar la falta de uniformidad de la aplicación del agua de riego.

10. El rendimiento del maíz mostró mayor variabilidad que la materia seca total. Ambas variables tuvieron más variabilidad que el agua aplicada estacional. Los riegos de baja uniformidad realizados a partir de la fase de floración mostraron una correlación significativa ente la dosis de riego y el rendimiento final en cada punto de la parcela experimental.

Al Objetivo 3 (Capítulos 4 y 5).:

11. El modelo *AdorSim* que combina un modelo balístico del riego por aspersión en cobertura total (*Ador-Sprinkler*) y un modelo de cultivos (*Ador-Crop*) ha permitido simular la incidencia de la uniformidad de cada riego por aspersión sobre la producción de un cultivo de maíz.

12. Se encontró una relación entre los parámetros correctores del coeficiente aerodinámico y la velocidad del viento. Para velocidades de viento inferiores a 1,1 m s^{-1}, la corrección del coeficiente aerodinámico no fue necesaria.

13. La validación de *Ador-Sprinkler* con los resultados del experimento descrito en el Capítulo 3 resultó satisfactoria. El valor medio del error cuadrático medio (*RMSE*) entre la aplicación de agua medida y simulada (0,95 mm h^{-1}) resultó comparable al *RMSE* medio entre las distribuciones medidas del agua de riego en los dos marcos experimentales (0,63 mm h^{-1}).

14. Los resultados de las simulaciones realizadas con *Ador-Crop* fueron muy similares a los obtenidos con el modelo *CropWat* (Smith, 1993). Puesto que el modelo propuesto incorpora el cálculo de la duración de los periodos de desarrollo del cultivo en base a tiempo térmico, resulta muy adecuado para simular el rendimiento de los cultivos en series temporales plurianuales.

15. La simulación de la reducción del rendimiento del maíz con *AdorSim* permitió explicar un 25 % de la variabilidad medida en campo. Aunque estos resultados son modestos, la representación del agua disponible para el cultivo frente a la reducción del rendimiento medido y simulado permitió identificar un comportamiento similar. Otros factores no considerados en *AdorSim* redujeron el rendimiento del maíz.

16. El modelo AdorSim permitió cuantificar el efecto de distintos marcos de aspersión sobre el rendimiento de un cultivo de maíz en las condiciones del valle del Ebro. Entre

los marcos habituales, la diferencia de rendimiento de un cultivo de maíz con el mismo volumen de agua de riego supera el 10 %.

17. El modelo AdorSim permitió cuantificar el efecto de la hora de comienzo del riego sobre el volumen de agua utilizada para cubrir las necesidades hídricas de un cultivo de maíz en dos localidades con importantes diferencias en su exposición al viento en el valle del Ebro (Zaragoza y Tamarite, con velocidades respectivas medias de viento de de 2,4 y 1,2 m s^{-1}). Los riegos diurnos consumieron más agua que los nocturnos. Esta diferencia resultó más marcada en la localidad más ventosa (Zaragoza), en la que además el cultivo necesitó más agua de riego para completar su ciclo.

18. Mediante la utilización del modelo AdorSim se determinaron valores umbrales de la velocidad del viento a los que se puede efectuar el riego por aspersión en las dos localidades estudiadas optimizando el rendimiento del maíz y el uso del agua. En las condiciones de Zaragoza, un umbral de 2,5 m s^{-1} resultó adecuado, mientras que en Tamarite el umbral fue de 2,0 m s^{-1}.

RECOMENDACIONES PARA LA INVESTIGACIÓN FUTURA

Los resultados de esta tesis sugieren que es preciso continuar con el análisis del uso del agua en comunidades de regantes modernas, en las que será necesario cuantificar la calidad del riego y diagnosticar el estado general de su agricultura de regadío. En este sentido, y siguiendo las pautas que Dedrick et al., (2000) establecieron para los Programas de Mejora de la Gestión, será preciso prestar atención no sólo al diagnóstico del riego sino al de todo el sistema agrario. Por ello, en futuros trabajos de este tipo será necesario acompañar a la caracterización de la uniformidad y la eficiencia del riego, de datos agronómicos (como la producción de los cultivos, y su relación con el riego), sociales y medioambientales. Será preciso un elevado volumen de trabajo para caracterizar el uso del agua en los sistemas presurizados del valle del Ebro.

En cuanto al modelo propuesto, será necesario continuar con su desarrollo antes de que de él se puedan extraer conclusiones sólidas que puedan ser aplicadas a resolver los problemas de la agricultura de regadío. Algunos aspectos del modelo necesitan investigación adicional, como es el caso del tratamiento de las pérdidas de agua por evaporación y arrastre, o de la ecuación usada para el coeficiente de rozamiento en el aire de las gotas de agua. Asimismo se necesitarán experimentos de campo adicionales para poder simular el riego por aspersión en otras condiciones de diseño y funcionamiento. Respecto al modelo de cultivos, su utilización en su estado de simplicidad actual resultó adecuado para obtener respuestas rápidas a muchas cuestiones, pero en el futuro será necesario experimentar la utilización de un modelo más desarrollado. El modelo de cultivos utilizado no dispone de algunas características que serían muy necesarias, como la predicción directa del rendimiento (en lugar de la reducción del rendimiento), un tratamiento más elaborado del agua del suelo, o la posibilidad de simular aspectos medioambientales como el lavado de sales y nitratos. Finalmente, la longitud de las series meteorológicas disponibles en las localidades seleccionadas (7 y 5 años) para la aplicación del modelo constituye un factor limitante adicional para la precisión de los resultados.

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