Journal of Agricultural Engineering

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Please cite this article as doi: 10.4081/jae.2025.1694

Submitted: 10 January 2025

Accepted: 4 July 2025

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Abstract

Improving the efficiency of water use in irrigated areas where surface irrigation is practised is now a goal that must be pursued with persistence, given the effects of climate change on the reduction of surface water availability, especially in Mediterranean areas. The impact of a flexible irrigation booking mechanism on water savings in surface irrigated areas has been investigated in this paper. The water reservation system consisted of an advanced decision support system that linked farmers' requests with the availability of water supply from the irrigation agency. This system was tested as a demonstration project in a portion of a real surface irrigation district located in Northern Italy and the results were compared with those obtained in the second portion of the district where a rigid irrigation calendar was applied. The results showed that, on average over the irrigation season, about 30% of water savings can be achieved if a flexible mechanism of water distribution is adopted, with peaks that can reach up to 60% in wet seasons. Water use efficiency increased significantly from the rigid to the flexible part of the district. These findings demonstrate that transitioning to a more flexible approach to water allocation within surface irrigation districts can yield substantial water savings, thereby enhancing water use efficiency and promoting the sustainability of surface irrigation practices.

Key words: flexible irrigation system; flexible scheduling; border irrigation; DSS.

Introduction

The Decision Support Systems (DSSs) are widely diffused in smart/digital agriculture to improve production while minimizing the cost and resource utilization (Mohapatra and Rath, 2022). In the irrigation field, these systems typically provide information about the irrigation requirements using (and often combining) satellite, ground-based measurements, and agro-hydrological modelling (D'Urso *et al*., 2013, Belfiore *et al*., 2022, Giannerini and Genovesi, 2015).

These systems find fertile ground for their proliferation in contexts where water is available to the farmer with an 'on demand' service, or where farmers have the option of freely drawing water from wells with pump/pressure systems. In general, they are used where pressurised systems of water diversion, distribution, supply, and application are implemented at farm and irrigation district scale (Ventura *et al*., 2021). In Italy, for example, DSSs are widely used to support irrigation in agricultural areas located on the right bank of the Po valley (the latter is the largest irrigated agricultural area in the country, covering 47,000 km^2), in central and southern Italy, where horticulture, orchards and pressurised water distribution systems are prevalent (Giannerini and Genovesi, 2015). In the left part of the Po Valley, where maize, rice, permanent pasture and gravity surface irrigation systems predominate, the use of DDSs for irrigation is not very common. A key limitation is that irrigation in these surface-irrigated areas is generally governed by a rigid calendar (water rotation), which restricts farmers' ability to make independent decisions about when to irrigate. Additionally, the historical gravity distribution network of canals in the Po Valley has limited capacity to respond dynamically and rapidly to changes in boundary conditions, such as fluctuations in water levels and alterations in diversion or supply requests during the irrigation season. This inflexibility stands in stark contrast to the 'on-demand' irrigation management required for the effective implementation of DSSs.

DSSs are typically implemented in contexts utilizing drip and sprinkler irrigation methods (Barradas *et al*., 2012). However, the irrigation volume for each drip irrigation event is approximately five times lower than that of surface irrigation, while each sprinkler intervention uses about three times less water than surface method (Bhavsar *et al*., 2023). Furthermore, in Italy, approximately 60% of water resources allocated for irrigation are utilized in surface-irrigated areas employing surface irrigation methods. These factors collectively indicate that the impact of DSS on water conservation is likely to be limited, although this has yet to be quantitatively assessed.

Enhancing the flexibility of water distribution and allocation, even within gravity-fed irrigation systems, may be crucial for increasing the adoption of Decision Support Systems (DSS) in surface irrigated areas, while simultaneously fostering water conservation efforts (Masseroni *et al*., 2021). Automatic and coordinated systems of gates in the gravity-fed irrigation distribution network have been used for decades in southern Australian regions (e.g., New South Wales, Queensland, *etc*.) to increase the flexibility of water allocation (and make it more in line with actual crop water needs), with very important results in terms of water savings (Koech *et al*., 2010, Hughes *et al*., 2012). Some applications of these coordinate system of gates are also present in EU agricultural contexts (e.g., Pina de Ebro irrigation district in Spain). In this pilot area, a telecontrol system enabled the irrigation agency to autonomously manage farm irrigation, leading to substantial reductions in water consumption and labor costs (Salvador Esteban *et al*., 2011). However, these modernization processes necessitate significant economic investments, often amounting to tens of thousands of euros per hectare, and the time required for large-scale implementation may not align with the ongoing decline in surface water availability in many Mediterranean agricultural regions (Giuliani *et al*., 2016). Therefore, a transitional phase combining infrastructure modernization with improved management of agricultural water use is essential. In this context, a water booking system for farmers and irrigation agencies could provide a viable solution to mitigate the rigidity of the current water allocation framework, while ensuring that water supply better matches the actual crop water needs.

In light of the previous considerations, this study examines the water-saving potential of an irrigation reservation system (*CEPII - Centro Prenotazioni Interventi Irrigui*) built upon a DSS comprising two interconnected platforms—one for farmers and one for the irrigation agency. The CEPII system was tested in a real irrigation district in northern Italy, with active participation from both farmers and the irrigation agency.

Materials and methods

The study domain

The irrigation district where the CEPII system was tested is located in the Padana plain, a few kilometres south of Garda Lake. Its name is Ponte Trento Irrigation District and it has been the object of several studies on surface irrigation performances as reported in the works of Masseroni *et al*. (2024), Costabile *et al*. (2023), Masseroni *et al*. (2022), Masseroni *et al*. (2021).

Specifically, the Ponte Trento irrigation district (Figure A, Supplementary Material) covers an area of about 130 hectares and consists of about 70 fields border irrigated, mainly cultivated with maize and permanent meadow on sandy/sandy loam soils. The average field size is about 1.5 ha, with maximum lengths not exceeding 200 metres. Water for irrigation is taken from the Virgilio canal (the main channel deriving up to 24 m^3/s from the Mincio river) and distributed to the fields in the district with a rigid rotation calendar of about 7 days. The theoretical flow rate available to each farmer to irrigate his fields is about 360 l/s with a on average duration of about 52 min/ha.

The diversion point on the Virgilio canal is equipped with an automatic FlumeGate® (Rubicon Water, AU) capable of maintaining a constant water supply to the district at the nominal flow rate and measuring the actual flow rate through the gate itself. Downstream of the diversion point, a hydraulic separator node distributes the flow rate to two portions of the irrigation district (Figure 1). One of the two parts is approximately 25 ha and consists of 13 fields managed by 5 farmers and was managed by using the CEPII system and a flexible water supply (‘experimental district’ in the Figure 1), while the remaining part of the Ponte Trento irrigation district remained under a rigid rotation of water distribution.

Downstream of the hydraulic divider (and towards the area irrigated by the CEPII system), an area-velocity flow meter (Sontek-IQ series, Standard model, Xylem) was installed at the bottom of the distribution channel to measure the actual water consumption of the experimental district (Figure B, Supplementary Material). The differences between the irrigation volumes measured by FlumeGate® and those monitored by the area-velocity gave the water consumption of the portion of the district under rigid rotation. Finally, an agro-meteorological station (ATMOS 41, Meter Group®, USA) has been installed at the head of the Ponte Trento irrigation district to monitor the main agro-hydrological parameters (rainfall, air temperature and humidity, solar radiation, wind speed).

The CEPII system

The CEPII system is based on two interconnected DSS platforms (Figure 2), one for farmers in the experimental district and one for irrigation agency technicians. The main difference between this DSS and the previous one in the literature is that CEPII is tailored to surface irrigation practices. It helps farmers decide 'when' to irrigate and enables (and manages) the dynamics of water allocation for the irrigation agency. In both cases, human experience is incorporated into the decision-making processes, for example, at the farm level the farmer can decide on the duration of each irrigation event (and then the irrigation volume), and at the irrigation district level the irrigation agency technicians can decide how to prioritize reservations.

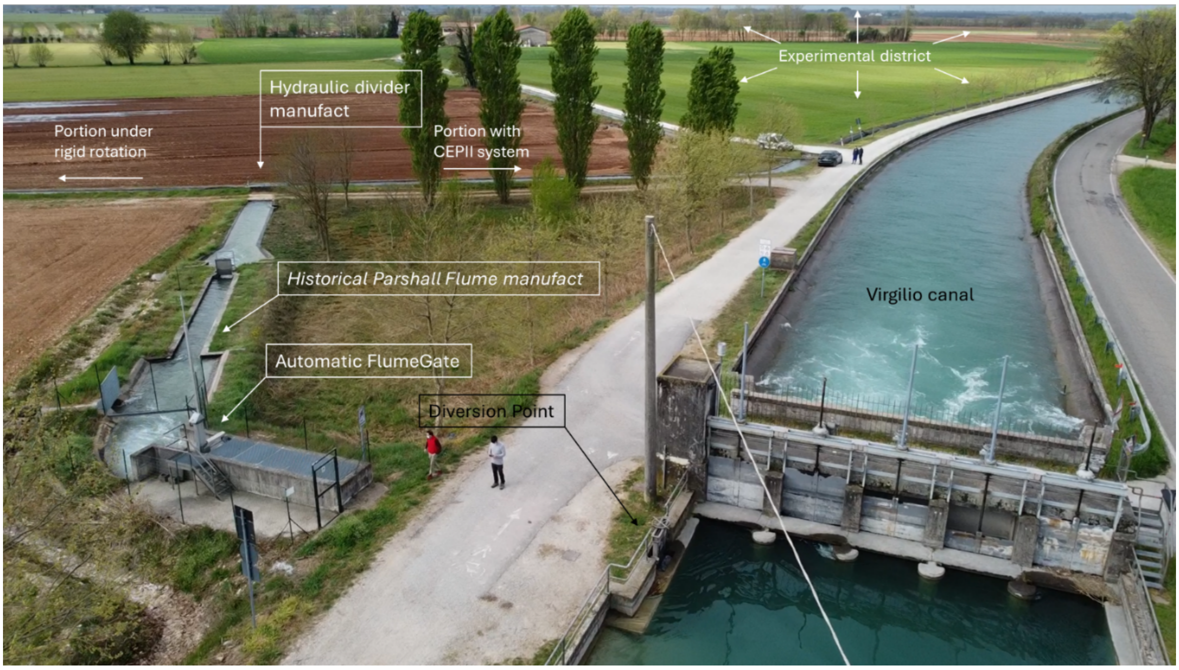

Figure 1. Aerial photograph of the head of the Ponte Trento irrigation district. The picture shows the Virgilio canal, the diversion point, the hydraulic divider, and the experimental part of the district where CEPII system was adopted.

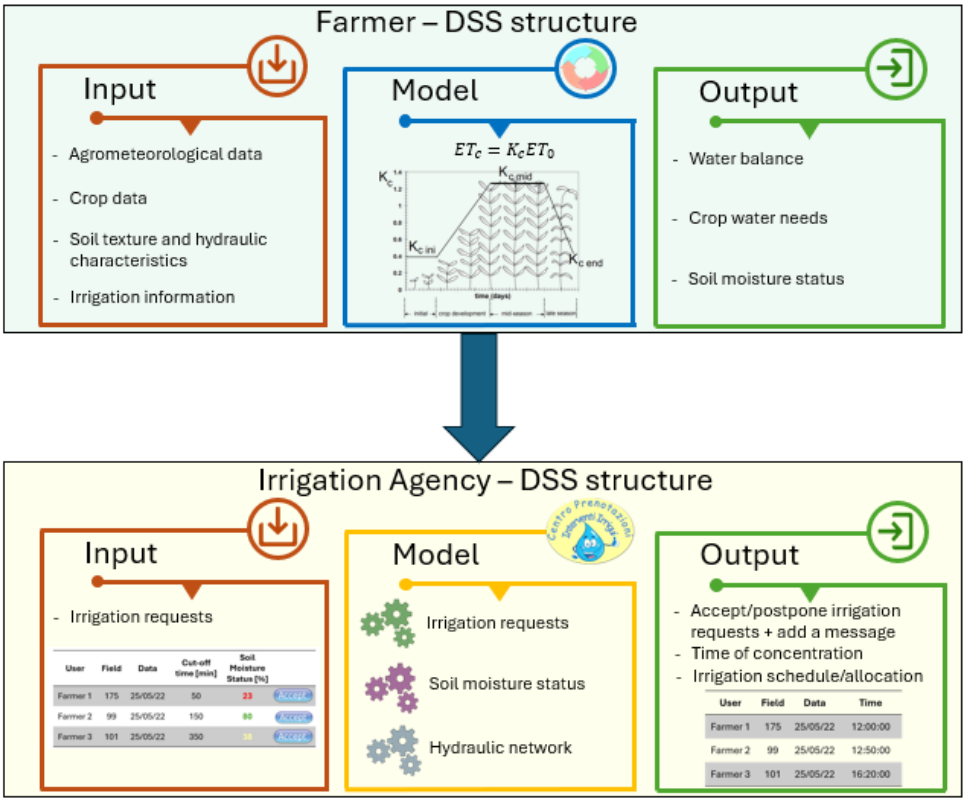

Figure 2. Logical architecture of the CEPII system.

Website architecture

Each user (farmer or irrigation agency) enters his own web page with a predetermined username and password.

In the farmer's web page (Figure 3), the user visualises the main information he normally uses to decide whether to irrigate. In particular, it is supported by i) the four-day rainfall forecast (taken from the main free downloadable rainfall forecasting services - https://openweathermap.org/api), ii) the estimation of the soil water status in the field represented by a simplified fuel level gauge (derived from the results of a single-crop coefficient FAO56 water balance model), iii) the chronological list of previous irrigations.

Each farm can customise its web page by selecting the field and crop, as well as the sowing date (e.g., for maize) or mowing date (e.g., for grass/permanent meadow).

Achieving the target water depth uniformly across a field using surface irrigation practices is significantly influenced by i) the available flow rate, ii) variability in soil characteristics, iii) the field's geometry and microtopography, and iv) land preparation methods (e.g., slope, ridges, furrows) (Masseroni *et al*., 2024). Consequently, a farmer's experience is essential in determining the appropriate amount of irrigation to apply. For this reason, the CEPII farmer web page allows farmers to specify the optimal duration of the irrigation event based on their expertise, as the flow rate typically remains constant throughout the irrigation process and aligns with the capacities of the irrigation agency's water distribution infrastructure. Once the duration of the irrigation event is entered, the algorithm calculates the average irrigation depth that the farmer would apply to the field with the selected duration.

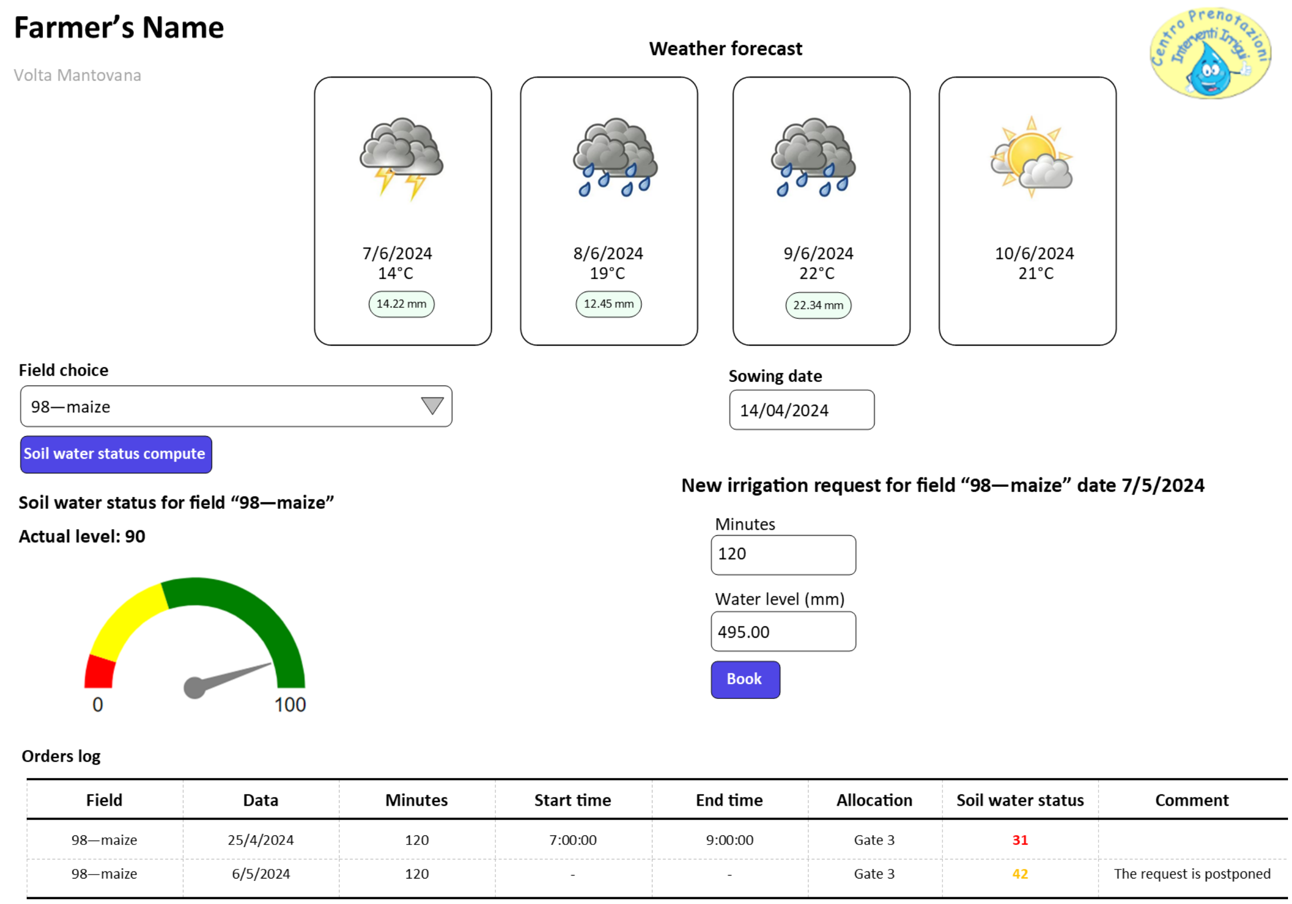

Figure 3. Example of the farmer front-end layout of the CEPII system.

The CEPII irrigation agency web page (Figure 4) is organized in three boxes, where there are three levels of organisation of irrigation requests. In the first box, the irrigation agency visualises all irrigation bookings in the experimental area on a daily basis. Specifically, in this pilot study, farmers had to submit the water request by 12 noon, while the irrigation agency processed all requests and provided feedback in the afternoon. Then irrigation agency decides whether to approve or reject the request, adding possible comments in the latter case. The decision is supported by the visualisation of the estimated soil water status for the field for which water is required. The comments made by the irrigation agency on the individual requests are displayed directly on the web page of the farmer. The approved requests reach the second level of data organisation, where an algorithm optimises the allocation of water requests according to the topological position of the fields in relation to the diversion point (i.e., the head of the irrigation district). Additionally, the algorithm uses the geometry of the irrigation canal network to calculate the concentration time between the diversion point and the head of each field. This information is then encoded into a calendar of irrigation sequences, which is communicated to farmers on their web page. After waterings, all requests are archived (third level).

Data analysis

The performance of the CEPII system was evaluated by comparing the measured irrigation volumes used in the flexible and rigid portions of the Ponte Trento irrigation district in the 2023 and 2024 agricultural seasons. Water use efficiency, as proposed by Bouman *et al*. (2005) and Fernandez *et al*. (2020), was also calculated in both parts of the irrigation district. In addition, the assessment of the potential water savings from the flexible water allocation mechanism obtained by using the CEPII reservation was calculated using the last 31 years of meteorological data (from 1993 to 2024).

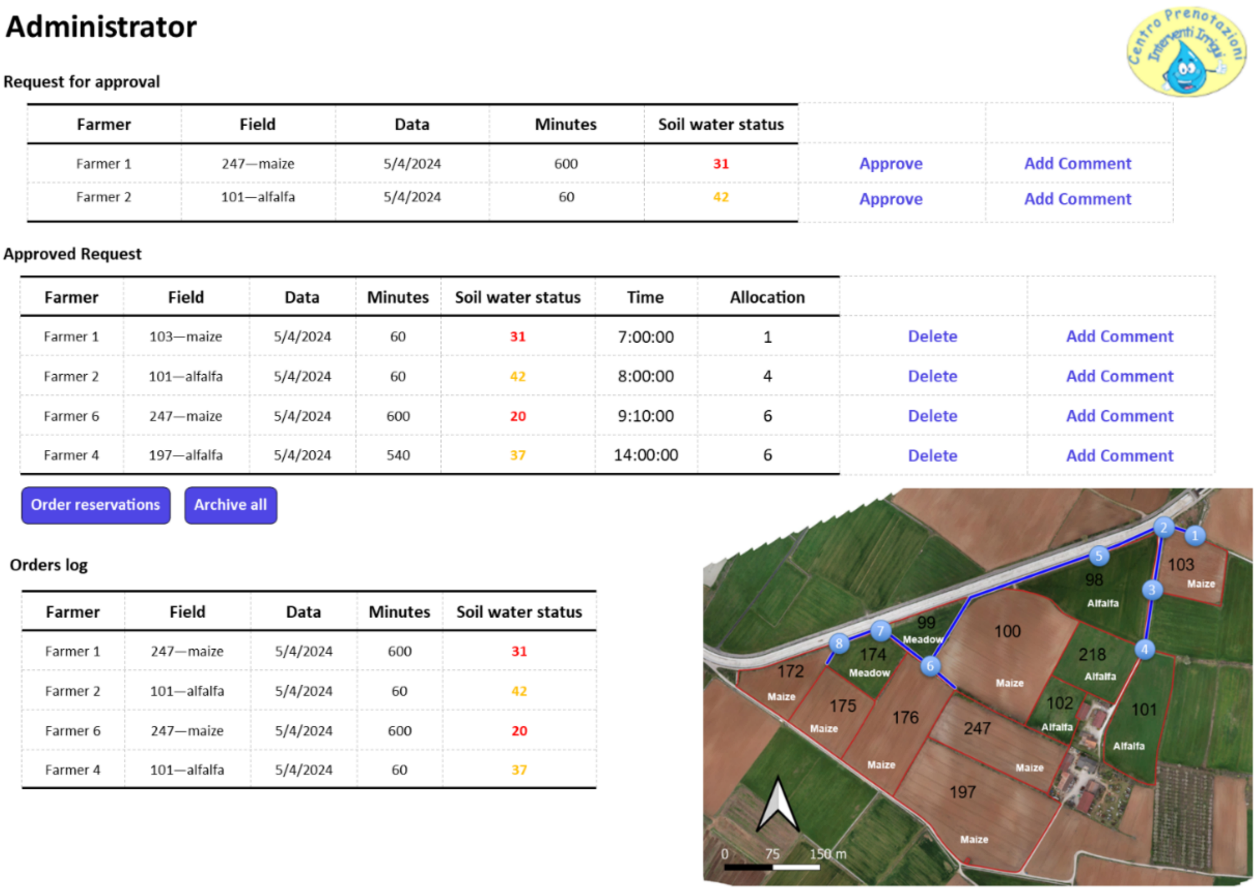

Figure 4. Example of the irrigation agency front-end layout of the CEPII system.

Results

Impact of the CEPII system on water saving

The comparison between the measured irrigation volumes aggregated on a monthly time scale used in the flexible and rigid parts of the Ponte Trento irrigation district in the 2023 and 2024 agricultural seasons is shown in Figure 5. The figure also shows monthly rainfall patterns and volumes.

In general, the possibility of reserving water through the CEPII portal allowed significant water savings in both agricultural seasons. Specifically, 42% of the water volume per unit area was saved in the flexible part of the irrigation district in 2023 and 59% in 2024 compared to the rigid part of the irrigation district. This very significant water saving is also a consequence of the fact that the rainfall during the irrigation season (i.e., from April to September) in the two years under consideration (around 400 mm in total per year) was about twice as high as the historical average rainfall (which is around 200 mm from 1993 to 2024). Both seasons can be considered, on average, as wet years (although in July and August 2024 the rainfall depth was only 20 mm each month compared to the historical average of almost double), a situation in which the application of a flexible water distribution mechanism (as opposed to a rigid one) can achieve the maximum water saving potential (Masseroni *et al*., 2021, 2022).

Significant differences in irrigation volumes applied in the flexible and rigid part of the Ponte Trento irrigation district was recognized in all months of the irrigation season. In general, the irrigation volume pattern observed in the flexible part of the irrigation district was more closely related to the rainfall pattern than in the rigid portion. This means that farmers in the flexible part of the district (i.e., where a flexible water supply mechanism was applied) paid more attention to the potential of rainfall to meet crop irrigation needs. This behavior helped to increase the efficiency of water use. Specifically, the annual water use efficiency (WUE), calculated as the ratio of crop evapotranspiration (using the Penman-Monteith equation) to the combined volume of rainfall and applied irrigation, was 7 percentage points higher in the flexible portion of the district compared to the rigid section in 2023, and 16 percentage points higher in 2024 (Table 1).

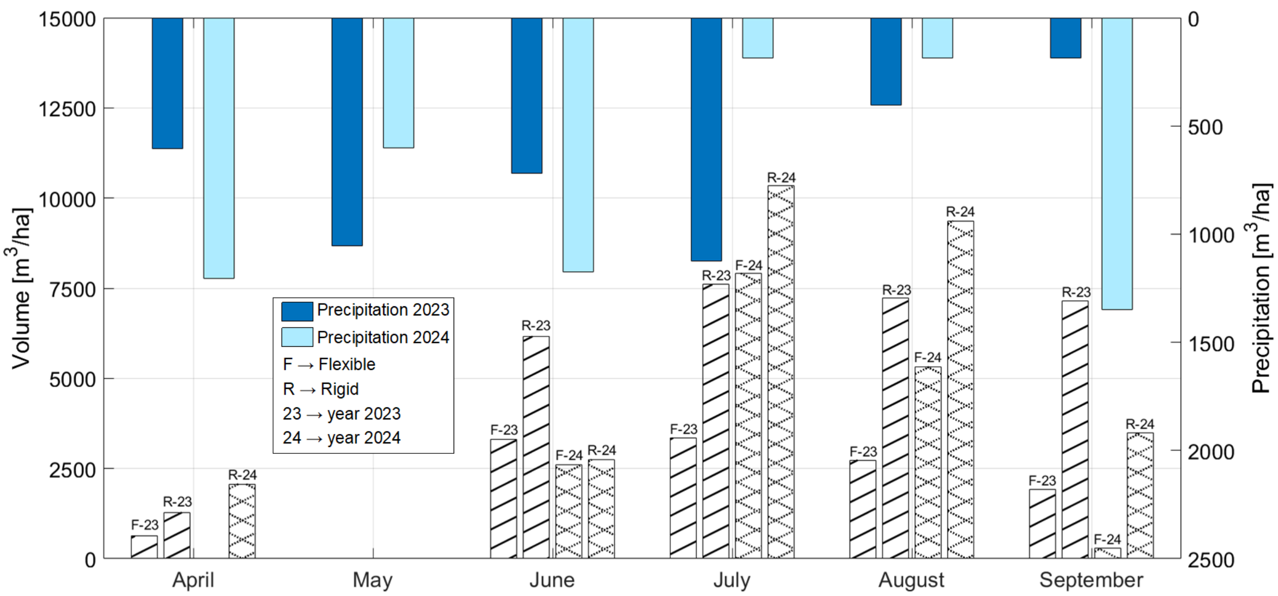

Figure 5. Comparison of measured irrigation volumes (cumulated on a monthly time scale) between flexible and rigid parts of the Ponte Trento irrigation district in the 2023 and 2024 agricultural seasons. Rainfall amounts are also shown in the image.

Table 1. Seasonal irrigation volume (I), crop evapotranspiration (ET), rainfall (R), and water use efficiency (WUE) in the flexible and rigid part of the Ponte Trento irrigation district in year 2023 and 2024.

Year	District	[I] (mm)	[ET] (mm)	[R] (mm)	[WUE] (%)
2023	**Flexible**	1611	395	470	19
	Rigid	2800	395	470	12
2024	**Flexible**	1194	482	409	30
	Rigid	2943	482	409	14

Irrigation volumes applied on experimental district

A focus on water uses in each field of the experimental district (i.e., the flexible portion of the Ponte Trento irrigation district) is reported in Figure 6. The average irrigation depth over the two monitored years was approximately 230 mm, but there is considerable variation between fields. In general, we observed that irregular fields (i.e., fields that are not squared or rectangular) required a long time to be surfaced irrigated (e.g., field 98, 99, 100, 174, 197). This is mainly due to the arrangement of the water inlets for each field, which are located on the head ditch. Each inlet feeds one sector (typically called a border); if the field is irregular from a geometrical point of view, one (or more) sector(s) will also be irregular (generally sectors were 20 m wide and irrigated at approximately 18 l/s/m), thus requiring additional time (and then volume) to achieve uniform water distribution across the field during the irrigation event.

Topographical irregularities, land preparation and irrigation practices (i.e., how the farmer manages watering during the irrigation event) were found to have a very significant impact on the amount of water used for irrigation. This is particularly evident in field 197 (grown with maize), which is characterized by significant topographic irregularity with more than 1m of elevation change over 180m length between the head and tail of the field. This is well illustrated in Figure 7, which shows a 3cm resolution Digital Terrain Model (DTM) of the field (obtained by a photogrammetric UAV survey). The actual DTM was then compared to a theoretically inclined plane with a slope equal to the average slope of the field (about 0.005 m/m). This comparison also revealed strong irregularities not only in the longitudinal direction, but also in the transverse direction. This could justify an irrigation depth of approximately 1.4 times the average irrigation depth used in the other maize fields in the experimental area (i.e., about 231 mm).

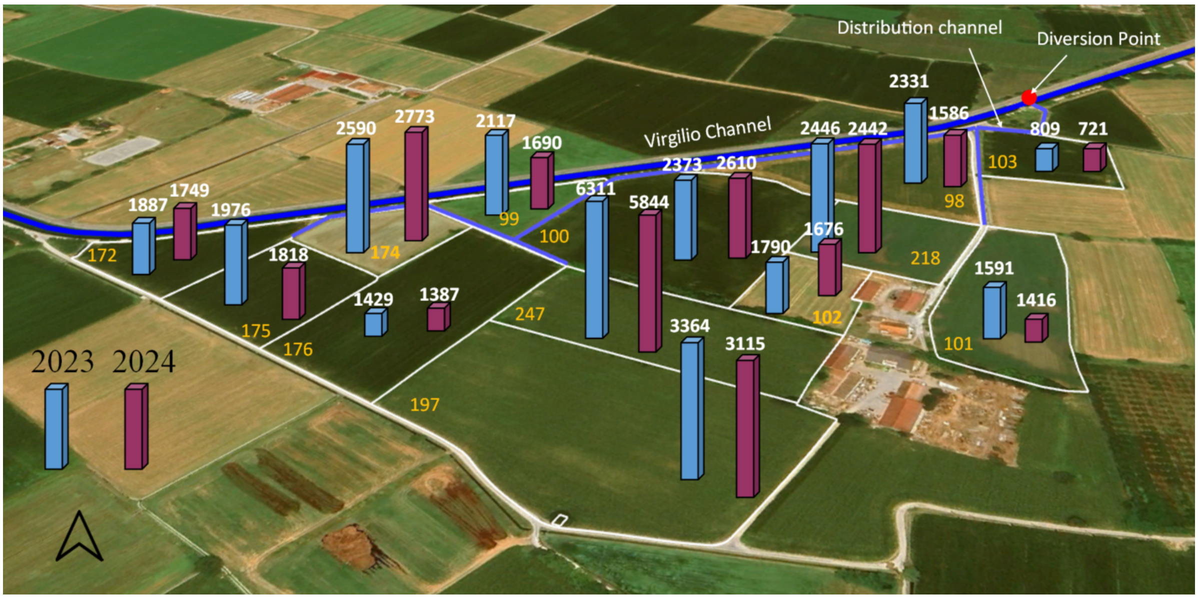

Figure 6. Irrigation volumes (expressed in m^3/ha) applied on average for each irrigation intervention on each field in the experimental area (i.e. the flexible part of the Ponte Trento irrigation district). The data were collected using the CEPII system. The number in yellow represents the field ID. The blue and violet histograms represent the irrigation volumes in the years 2023 and 2024 respectively.

Irrigation management is another factor affecting water use. A case in point is field 247 (grown with maize), which received an average of around 600 mm per irrigation event (i.e., about 3 times greater than the average irrigation depth used in the other maize fields in the experimental area), even though it doesn't have any significant geometrical or topographical irregularities. The lack of control systems to directly manage the opening and closing of inlets gave the farmer considerable flexibility. This often results in excessive water application compared to actual needs (as already observed by Masseroni *et al*., 2024).

An example of how good control of inflow times can improve water savings can be seen in field 176 (grown with maize). This field has been instrumented since 2023 with automatic gates at each inlet point (as better described in the work of Costanzo *et al*., 2024). The volume of water applied was, on average, 1.8 times lower than the average volume applied in the maize fields of the experimental area where no automation of the inlets was applied.

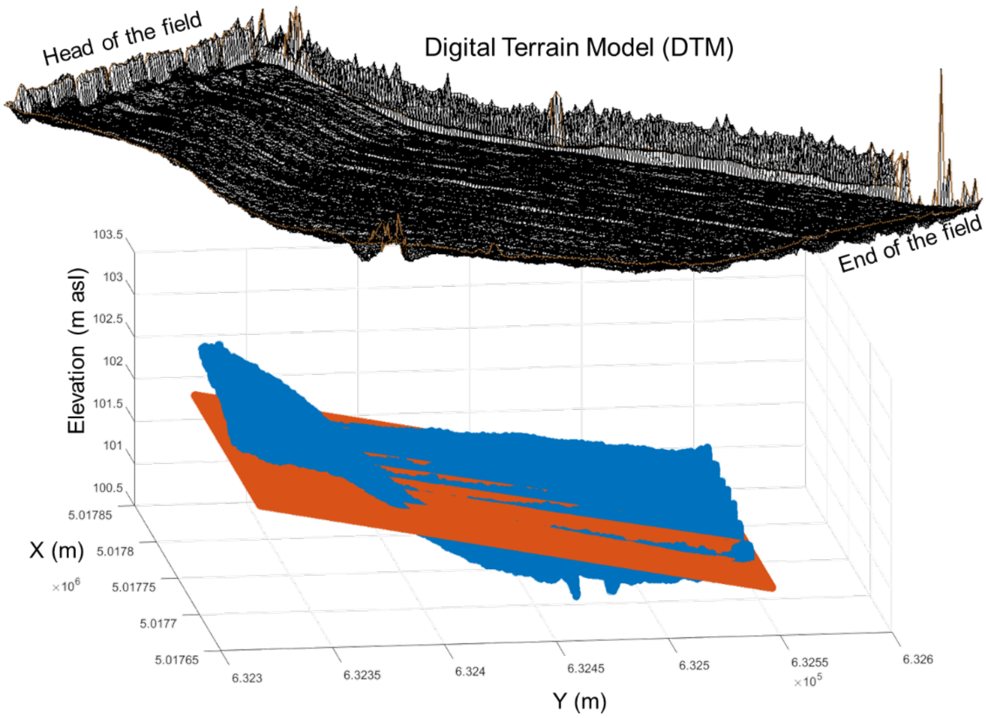

Figure 7. Digital terrain model (DTM) with a ground resolution of 3 cm, obtained by a photogrammetric UAV survey of field 197. The comparison between the actual DTM (blue one) and the theoretical regular slope (orange one) gives an indication of the geometric and topographical irregularities in the three cardinal directions.

Finally, the use of good land preparation practices (e.g., dividing the field into sectors) was found to result in significant water savings. This is the example of field 98 (cultivated with maize) where the water saving after sectoring (carried out in the 2024 agricultural season - Figure 8) was approximately 32%.

However, it is not always possible to divide the field into sectors. This case pertains to grass or permanent meadow (e.g., fields 99, 174, and 102), where ridges are typically not constructed to facilitate cutting operations. Consequently, the time required for irrigation in our case study is significantly greater than that for maize - approximately 20% longer in the experimental district. This increase can be attributed not only to the lack of field division into sectors but also to the high resistance to flow presented by the vegetation, which fully covers the ground surface.

Discussion

Simulation of the impact of the CEPII system on long-term water savings

In order to evaluate the potential of the flexible irrigation reservation system experimented in this work over a long period of time (i.e., taking into account several agricultural seasons), a comparison between the irrigation needs of the flexible and the rigid part of the Ponte Trento irrigation district was carried out through a water balance simulation using 31 years of meteorological information between 1993 and 2024. Specifically, the model, based on the FAO56 single crop coefficient approach, was calibrated on a monthly time scale, comparing observed and simulated water volumes at the head of the two sub-districts (i.e., the flexible and the rigid) in the year 2023 (the results of calibration procedure are reported in Figure C, Supplementary Material). Based on observations, in the flexible part of the irrigation district, the irrigation event was triggered when about 75% of RAW was depleted in the case of meadow, while for maize when about 50% of RAW was depleted in the initial stage, about 70% in the development stage and about 80% in the maturity-senescence stage. For each irrigation event, the irrigation depth was considered equal to the average of those observed in the district (i.e., about 230 mm). A 10% water loss along the distribution network was considered in order to bring the irrigation needs back to the head of the district (this value was confirmed by the irrigation agency). The same irrigation depth and water losses were also considered for the rigid part of the district, while irrigation interventions were limited to once a week (in accordance with the irrigation district calendar) and carried out only when about 30% of the RAW was depleted (as observed in 2023). This indicates that farmers have an extremely risk-averse attitude when operating under a rigid-rotation irrigation schedule.

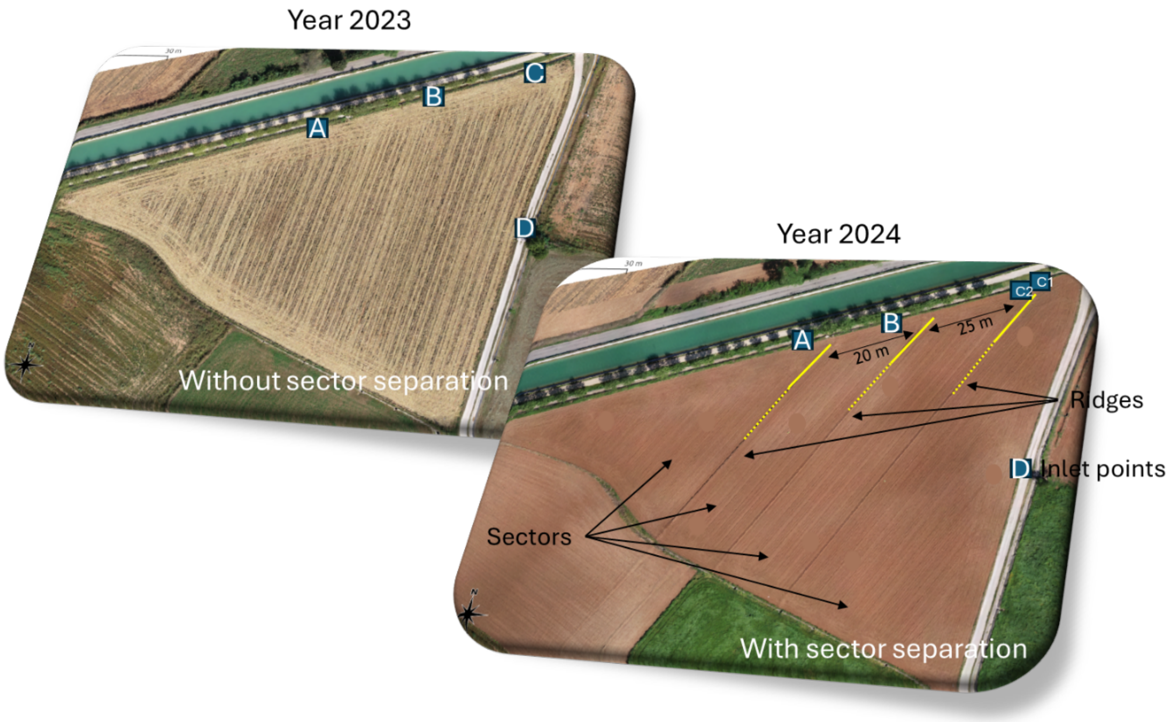

Figure 8. Land preparation of field 98 in the year 2024. The first image captures the field just after the maize harvest in 2023, while the second image captures the field just after the sowing in agricultural season 2024 and its division into sectors.

The results of this simulation are reported in Figure 9. Long-term water saving using a flexible irrigation booking mechanism was in general about 30% (on the entire irrigation season) compared to a rigid calendarization of irrigation interventions. However, the interannual variability in irrigation demand (represented by the whiskers in the figure) can lead to a situation where the amount of irrigation applied in the flexible and rigid parts of the irrigation district is more or less the same (i.e., where the whiskers overlap). This behavior was even more pronounced during drier seasons. In these cases, if the rigid irrigation calendar is well calibrated, the number of irrigations in both parts of the irrigation district will be about the same. This behavior is consistent with the results reported by Masseroni *et al*. (2024) at the field scale. In their study, two fields in the Ponte Trento irrigation district, each divided into two sectors irrigated by 'on-demand' and 'rigid rotation' mechanisms, showed that in a wet year (such as 2021), approximately only five irrigation events were applied in the 'on-demand' part of the field, compared to eleven in the 'rigid rotation' part. In contrast, in a dry year (such as 2022), the differences in the number of irrigation operations were minimal (about eight in both parts).

An additional simulation was carried out to investigate the potential water savings of a flexible water distribution system integrated with a 2-day rainfall forecast. This approach allowed the model to avoid inappropriate irrigation just before significant rainfall events (defined in this simulation as greater than 10 mm per day). This approach was implemented to more accurately replicate farmers' decision-making processes regarding the timing of irrigation. The results, shown in Figure 9 (green line), indicate that during the initial irrigation period (from April to June), one or two irrigation events on average could generally be avoided, taking advantage of rainfall events to satisfy the relatively low crop water requirements. From July to the end of the irrigation season, the timing of irrigations could be adjusted throughout the month, but the total number of irrigation events—and consequently the irrigation volumes—remained unchanged.

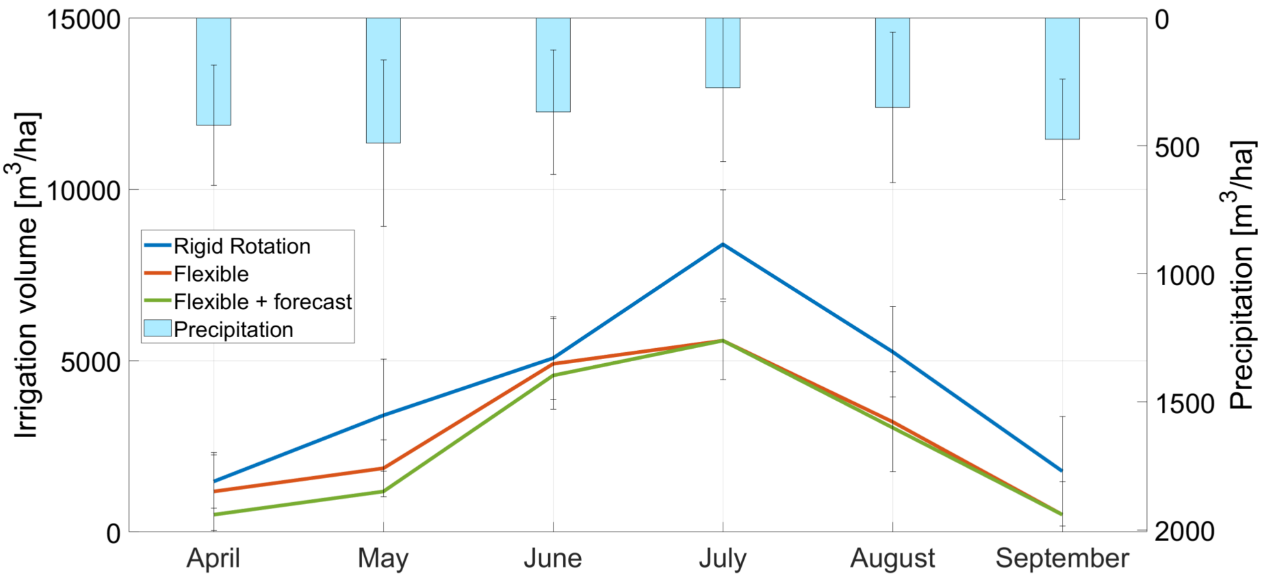

Figure 9. Simulation of monthly irrigation volumes applied in the flexible and rigid parts of the Ponte Trento irrigation over 31 years of meteorological data (from 1993 to 2024). In particular, the histograms represent the rainfall, the blue line (rigid rotation) and red line (flexible) represent the pattern of irrigation volumes applied in the rigid and flexible parts of the district, respectively. The green line (flexible+forecast) represents the irrigation volumes derived from a flexible water distribution system integrated with a 2-day rainfall forecast. The wiskers represent the variability of the monthly amounts shown between years.

Conclusions

This work investigated the potential of an irrigation booking system (called *CEPII - Centro Prenotazioni Interventi Irrigui*) in a surface irrigated area. The innovative aspect of this booking system is that it links farmers' requests with the availability of water supply from the irrigation agency. The water saving potential derived by the adoption of this system was compared with the water uses occurred in a traditional portion of the surface irrigated area under a rigid rotation calendar, over two agricultural seasons. The results were very promising, with water savings of more than 30% where flexible irrigation was used, and an significant increase in water use efficiency.

Based on our observations, we can conclude that in areas where surface irrigation is used, increasing the flexibility of irrigation scheduling, rather than adhering to a rigid calendar, can lead to significant water savings. Transitioning from a rigid irrigation calendar to a booking system can be challenging in surface irrigated areas - especially where water distribution infrastructure is limited or not well organized - and requires close cooperation between farmers and irrigation agencies. However, this approach offers the potential to reduce irrigation volumes and improve the sustainability of traditional surface irrigation practices.

Data Availability

Data will be made available on request.

Acknowledgements

This study was developed in the context of:

IrriGate project “Toward a smart and flexible irrigation management in gravity-fed irrigation contexts” funded by Regione Lombardia (PSR 1.2.01 operation) year 2019—Grant no. 201901319885.

IrriSuS project “Sustanible Surface Irrigation” funded by Regione Lombardia (PSR 1.2.01 operation) year 2022—Grant n. 202202220204.

Agritech National Research Center and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR)—MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4—D.D. 1032 17/06/2022, CN00000022).

CSIS project – “Certification of the Surface Irrigation” funded by Fondazione Cariplo grant n. 2023-3653

The authors would like to express their deep gratitude to the technicians of the Garda Chiese reclamation consortia and to the farmers of the Ponte Trento irrigation district for their support of the project.

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