

INTEGRATING IOT IN SURFACE IRRIGATION: A MODELLING APPROACH TO EVALUATE THE MODERNIZATION OF IRRIGATED LANDS

INTÉGRATION DE L'IOT DANS L'IRRIGATION DE SURFACE: UNE APPROCHE DE MODÉLISATION POUR ÉVALUER LA MODERNISATION DES PÉRIMÈTRES IRRIGUÉS

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ABSTRACT

Surface irrigation is the most widespread technique globally but is frequently characterized by low application efficiency and high labour demands. While performance can be improved by optimizing topography and plot size, human constraints often lead to the enlargement of plots to reduce workload, which further degrades efficiency. This study investigates the redesign of surface irrigation schemes by integrating Internet of Things (IoT) tools, such as low-cost sensors and remotely-operated gates, to balance labour reduction with water conservation. The research utilizes an integrated modelling approach via the agro-hydrological model Openfluid, employing the specific 'IrriSurf' module to simulate water flow across plots and channels. This methodology was applied to an experimental site in the Crau region of southern France, where 14,000 hectares of hay meadows typically receive high water volumes (20,000 m³/ha) with efficiencies often below 40%. The study monitored the irrigation season (2022–2023) using pressure probes and surveys to calibrate the model against actual practices. Simulations of alternative designs demonstrate that equipping plots with sensor-controlled gates can significantly increase application efficiency without increasing the irrigator's workload. The model successfully evaluated the necessary irrigation time and water volumes lost through drainage for various configurations. Ultimately, this work contributes to the optimization of gravity irrigation by showing how digital decision support and automation can modernize traditional systems. By reconciling technical performance with operational feasibility, these findings provide a strategy for sustaining surface irrigation in the face of increasing water scarcity.

Keywords: Border irrigation, irrigation efficiency, agro-hydrological modelling, IoT, sensor-based irrigation control.

RÉSUMÉ

L'irrigation de surface est la technique la plus répandue dans le monde, mais elle se caractérise fréquemment par une faible efficacité d'application et d'importants besoins en main-d'œuvre. Bien que ses performances puissent être améliorées en optimisant la topographie et la taille des parcelles, les contraintes de main-d'œuvre conduisent souvent à agrandir les parcelles afin de réduire la charge de travail, ce qui dégrade davantage l'efficacité. Cette étude examine la reconfiguration des systèmes d'irrigation de surface par l'intégration d'outils de l'Internet des objets (IoT), tels que des capteurs à faible coût et des vannes télécommandées, afin de concilier réduction de la main-d'œuvre et économie d'eau. La recherche s'appuie sur une approche de modélisation intégrée au moyen du modèle agrohydrologique OpenFLUID, en utilisant le module spécifique « IrriSurf » pour simuler l'écoulement de l'eau dans les parcelles et les canaux. Cette méthodologie a été appliquée à un site expérimental de la Crau, dans le sud de la France, où 14 000 hectares de prairies de fauche reçoivent généralement d'importants volumes d'eau (20 000 m³/ha), avec des efficacités souvent inférieures à 40 %. La campagne d'irrigation (2022–2023) a été suivie à l'aide de sondes de pression et de relevés

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afin d'étalonner le modèle par rapport aux pratiques réelles. Les simulations de configurations alternatives montrent que l'équipement des parcelles en vannes commandées par capteurs peut accroître sensiblement l'efficacité d'application sans augmenter la charge de travail de l'irrigant. Le modèle a permis d'évaluer avec succès le temps d'irrigation nécessaire et les volumes d'eau perdus par drainage pour différentes configurations. En définitive, ce travail contribue à l'optimisation de l'irrigation gravitaire en montrant comment l'aide à la décision numérique et l'automatisation peuvent moderniser les systèmes traditionnels. En conciliant performances techniques et faisabilité opérationnelle, ces résultats proposent une stratégie pour pérenniser l'irrigation de surface face à une pénurie d'eau croissante.

Mots-clés : Irrigation par planches; Efficacité de l'irrigation; Modélisation agro-hydrologique; IoT; Contrôle de l'irrigation par capteurs.

1. INTRODUCTION

Gravity irrigation is the most widely used irrigation technique in the world (Pereira and Gonçalves, 2018). It involves applying water directly to the soil surface and allowing it to flow by gravity across the field. As a result, it is less energy-intensive than other irrigation techniques but requires more labor and more water. Consequently, gravity irrigation is considered the least efficient irrigation technique (Daccache, 2014; Pereira and Gonçalves, 2018).

Improving the performance of gravity irrigation has been the subject of further scientific research (Pereira et al. 2002; Burt et al. 1997). First, the concept of irrigation efficiency (IE) has been used since its introduction in the early 20th century (Israelson, 1950) in agro-hydraulic development engineering. Subsequently, several studies have identified avenues for improving the performance of gravity irrigation; González-Cebollada et al. 2016 studied topography optimization. Nie et al. 2021 and Anwar et al. 2016 investigated ways to optimize the size of irrigated plots and irrigation flow rates to improve irrigation performance.

To reduce the workload, irrigated plots are often enlarged, thereby reducing irrigation efficiency (Zerihun et al., 2005). Other studies have shown that adjusting the irrigation schedule based on irrigation rate and soil characteristics can improve irrigation performance and conserve water (Masseroni et al., 2024; Nie et al., 2019; and Morris et al., 2015). Improved irrigation efficiency could be achieved by increasing the irrigation rate up to a certain threshold (Smith et al., 2018; Smith and Uddin, 2020). Finally, the optimization practices employed by the irrigator—in this case, the optimization of shutoff times—have certain limitations due to spatio-temporal variations in infiltration and surface roughness (Xu et al., 2019).

The rise of the Internet of Things (IoT) provides new opportunities to overcome these limitations. Low-cost sensors can remotely detect the water front advance or changes in soil moisture, providing real-time decision support. When coupled with remotely operated gates, these digital tools make it feasible to manage smaller, highly efficient plots without increasing the irrigator's workload (Vandôme et al., 2024). However, experimentally testing multiple water management and plot redesign scenarios at the scheme scale remains challenging. Consequently, numerical simulation offers a powerful alternative (Merot et al., 2008). While 1D event-based models like SIRMOD (Walker, 2003), WinSRFR (Bautista et al., 2009), and SISCO (Gillies and Smith, 2015) are widely used at the plot scale, optimizing an entire scheme requires evaluating global efficiency across multiple plots, channels, and control strategies. To this end, Vandôme et al. (2025) recently integrated a specific surface irrigation module ('IrriSuf') into the agro-hydrological model OpenFLUID (Fabre et al., 2010), enabling the simulation of flow transfers, crop development, and sensor-based gate controls across a complete irrigation scheme.

Despite these advancements, assessing the benefits of IoT modernization under fluctuating field conditions (flow rate, leaf area index, roughness, and soil moisture) on a large scale extending beyond the plot level remains largely unexplored. Building upon the development of the IrriSuf agro-hydrological modeling platform, this study aims to evaluate and compare different modernization

strategies for gravity-irrigated systems. Specifically, we explore the deployment of low-tech sensors (sensor-based vs. time-based management) on both irrigation efficiency and water balance at the scale of an irrigated area.

2. MATERIALS AND METHODS

2.1. Study area

Located in southern France, the Crau irrigated territory covers an area of 600 km² and encompasses 14,000 hectares of meadows dedicated to hay production, which are watered using the border irrigation method. Water is supplied from the Durance River and distributed through an extensive network of open channels. Traditionally, the meadows are divided into irrigation borders—locally referred to as *calans*—with lengths ranging from 100 to 500 m and mild slopes between 0.2% and 0.4%. Irrigation is organized in rotations of 8 to 10 days, occurring from March to October, and is strictly managed by local water user associations (Merot et al., 2008a). The typical volume of water applied is highly abundant, averaging approximately 20,000 m³/ha per year, which generally results in a low irrigation efficiency of under 40% (Merot et al., 2008b). However, this massive water input plays a critical environmental role: it artificially recharges the Crau groundwater aquifer, which currently supplies drinking water to around 300,000 inhabitants. Consequently, any reduction in either the irrigation water volumes or the total surface area of the irrigated meadows directly impacts the aquifer's water table (Oliosio et al., 2013).

The present study was conducted at the Institut Agro experimental farm (43.643748 N, 5.016744 E, WGS84), a facility situated in the Crau plain that specializes in water management and hay production. Specifically, the research focused on "Sector 1" of the farm (Figure 1), which comprises several plots ranging from 89 m to 576 m in length. To evaluate different spatial configurations, the plots feature distinct geometries and orientations: *calans* 1G and 1K represent the traditional layout, measuring between 89 m and 98 m in length, and are irrigated laterally from east to west. In contrast, *calans* 1H, 1I, 1L, and 1M have been redesigned to form longer plots ranging from 289 m to 576 m, with irrigation advancing from north to south. Prior to the experiments, all the studied plots underwent land leveling to ensure a relatively homogeneous and constant longitudinal slope.



Figure 1: The study plots in Sector 1, Domaine du Merle

2.2. Methodology

The methodology is structured around three key steps: i) Data collection and processing: Gathering comprehensive agro-hydrological data, which includes irrigation durations and flow rates, climate data, and the physical characteristics of the *calans*. ii) Agro-hydrological modeling: Modeling hay irrigation for the monitored year, followed by the simulation of modernization scenarios under normal climatic

conditions. iii) Scenario analysis: Analyzing and comparing all scenarios based on irrigation efficiency and complete water balances at both the plot and sector scales.

To ensure the simulations accurately reflected actual field conditions, an extensive irrigation monitoring and measurement system was installed in Sector 1 of the experimental farm (Figure 1) throughout the 2023 season. This system utilized barometric pressure sensors deployed within the farm's low-pressure water distribution pipeline. The recorded pressure data were processed and visually interpreted to clearly distinguish periods of active irrigation from non-irrigation periods.

These sensor logs were subsequently cross-referenced with the irrigation schedules reported by the irrigator, enabling us to accurately assign specific irrigation durations and flow rates to their corresponding calans. Due to occasional missing sensor data during the early and middle stages of the 2023 irrigation campaigns, the continuous extraction of flow and timing information was occasionally interrupted. To address these data gaps, the sensor-derived schedules were successfully supplemented with reconstructed irrigation events based on detailed surveys and interviews conducted with the irrigator.

Finally, we modelled and compared the modernization scenarios: (i) traditional plots with conventional time-based cutoff management; (ii) traditional plots modernized with low-tech water sensors linked to automated gates. The performance of each scenario was rigorously evaluated using two key indicators: Application Efficiency (AE), water balance at sector level.

3. RESULTS AND DISCUSSION

The implementation of in-field sensors led to a substantial enhancement in irrigation application efficiency, which increase from a mean of 24,7% under traditional management to 41,2% with sensor-assisted control. This represents an absolute increase of over 16,5%. However, the adoption of sensors was also associated with increased performance variability, with the standard deviation rising from 16.7% to 25,1.2%. Despite this wider dispersion, efficiency peaks reached nearly 100% for certain events, demonstrating the potential for near-optimal water application when real-time data is used to overcome the unpredictability of surface flow.

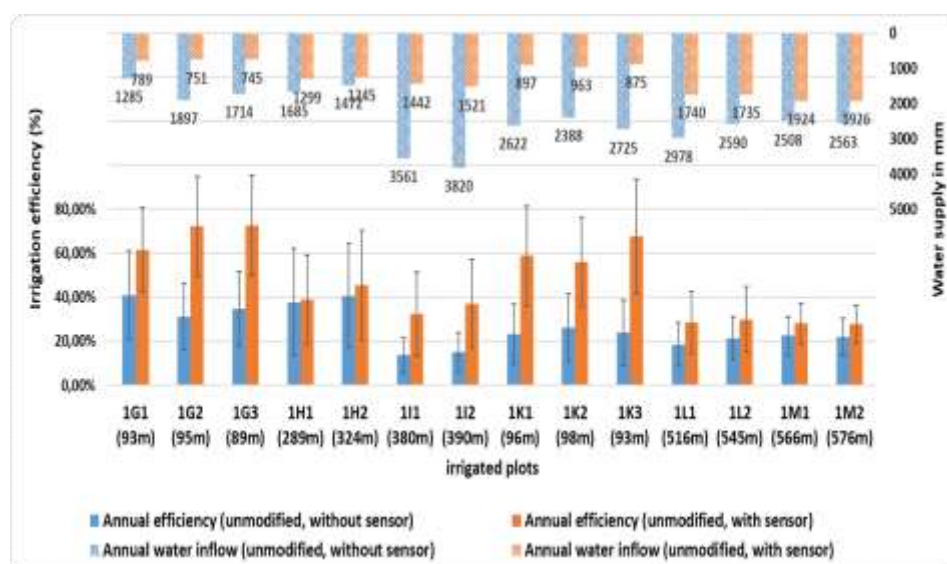


Figure 2: Comparison of annual mean efficiencies and annual water inflows for each plot under scenarios with and without sensor installation

The comparative analysis of the components of the water balance between time-based cutoff and sensor-based control highlights significant differences in the distribution of applied water. Figure 3a illustrates how the water applied to plots of varying sizes is distributed among water stored in the root zone, water that has percolated to the groundwater table, and water that has Runoff. First, the simulations show that the volume of water effectively retained in the root zone does not vary significantly between the two scenarios. Thus, despite a significant reduction in the total water volume injected in the instrumented scenario, the effective soil water reserve in the root zone is fully restored with each irrigation event.

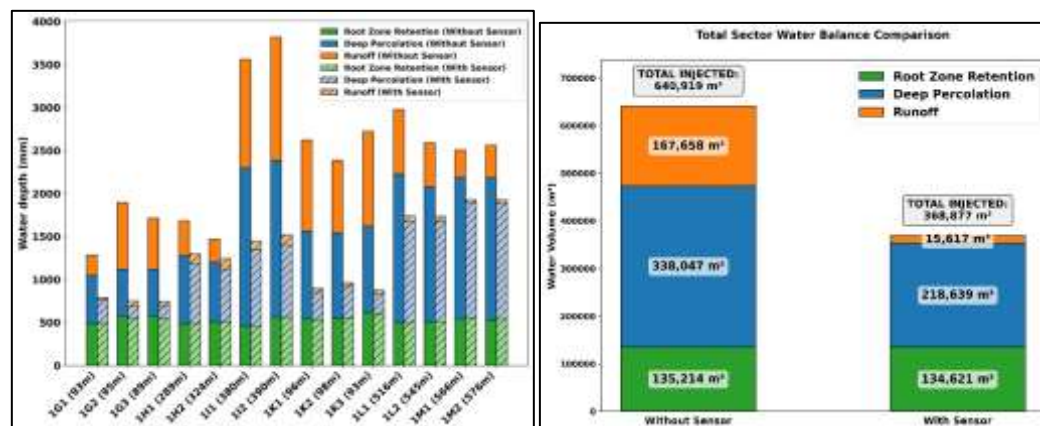


Figure 3 : a) Comparison of the annual totals of water retained in the root zone, percolated, and runoff (mm) at the level of each plot in the sector for scenarios with and without sensors. b) Comparison of the water volumes retained in the root zone, percolated, and runoff at the level of sector 1.

Furthermore, runoff and percolation below the root zone decreased significantly in the scenario where irrigation was controlled by sensors. The integration of sensors (e.g., the WatAr system) into irrigation control helps optimize the cut-off time (T_{co}) and irrigation time. For example, on certain plots equipped with sensors, Deep percolation depth can be reduced by nearly 48%, while surface runoff can be reduced by a factor of 13 compared to time-based cutoff (e.g., the runoff water depth decreased from 1,662 mm to 94 mm for plot 111).

4. CONCLUSION

These results highlight the importance of modernizing gravity irrigation by using low-tech sensors that alert farmers of when to cut off the water supply. In quantitative terms, sensor-based management enables substantial water conservation at an irrigated area, offering a flexible solution to significantly reduce irrigation water use and thereby address water shortages, which are becoming increasingly frequent, without compromising agricultural yields. This transition to “digital low-tech” paves the way for reconciling agricultural production with the conservation of water resources. By reducing the volume of drained water and runoff while maintaining a constant volume of root zone, irrigation efficiency is significantly increased. While traditional practices in the Crau area often yield between 14% and 41%, sensor-based management achieves much higher rates between 28% and 73% depending on the plot.

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