

A PLUG-AND-PLAY IRRIGATION MANAGEMENT SYSTEM BASED ON HYDRAULIC NETWORK MODELLING: TECHNICAL, OPERATIONAL AND ECONOMIC IMPACTS

UN SYSTÈME DE GESTION DE L'IRRIGATION PRÊT À L'EMPLOI FONDÉ SUR LA MODÉLISATION DES RÉSEAUX HYDRAULIQUES : IMPACTS TECHNIQUES, OPÉRATIONNELS ET ÉCONOMIQUES

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ABSTRACT

Agricultural irrigation management is facing increasing challenges related to water scarcity, rising energy costs and the growing complexity of irrigation networks. In many agricultural contexts, irrigation systems consist of heterogeneous infrastructures combining pumps, valves, pivots, drip irrigation, fertigation units and multiple sensor technologies. Despite this level of equipment, irrigation is still frequently managed empirically, with limited visibility on the actual hydraulic behaviour of the network. This lack of understanding often results in water losses, excessive energy consumption, uneven water distribution and delayed corrective interventions.

This paper presents an Irrigation Management System (IMS) based on dynamic hydraulic modelling of irrigation networks combined with real-time field data integration. The system is designed as a plug-and-play solution compatible with existing infrastructures. A hydraulic digital twin is used to simulate and monitor network performance. Field deployments across multiple regions demonstrate water savings of 10–25%, energy savings of 10–20%, and a return on investment within 12 to 18 months. The system also improves operational management of field teams, increasing responsiveness and irrigation reliability.

Keywords: Agricultural irrigation management; Water scarcity; Rising energy costs; Corrective interventions; Irrigation reliability.

RÉSUMÉ

La gestion de l'irrigation agricole est confrontée à des difficultés croissantes liées à la rareté de l'eau, à la hausse des coûts énergétiques et à la complexité grandissante des réseaux d'irrigation. Dans de nombreux contextes agricoles, les systèmes d'irrigation reposent sur des infrastructures hétérogènes combinant pompes, vannes, pivots, irrigation goutte à goutte, unités de fertigation et diverses technologies de capteurs. Malgré ce niveau d'équipement, l'irrigation reste souvent gérée de manière empirique, avec une visibilité limitée sur le comportement hydraulique réel du réseau. Cette méconnaissance entraîne fréquemment des pertes d'eau, une consommation énergétique excessive, une répartition inégale de l'eau et des interventions correctives tardives.

Cet article présente un système de gestion de l'irrigation (IMS) fondé sur la modélisation hydraulique dynamique des réseaux d'irrigation, combinée à l'intégration de données de terrain en temps réel. Le système est conçu comme une solution prête à l'emploi, compatible avec les infrastructures existantes. Un jumeau numérique hydraulique est utilisé pour simuler et surveiller les performances du réseau. Des déploiements sur le terrain dans plusieurs régions montrent des économies d'eau de 10 à 25 %, des économies d'énergie de 10 à 20 % et un retour sur investissement en 12 à 18 mois. Le système améliore également la gestion opérationnelle des équipes de terrain, en renforçant leur réactivité et la fiabilité de l'irrigation.

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Mots clés : Gestion de l'irrigation agricole; Rareté de l'eau; Hausse des coûts énergétiques; Interventions correctives; Fiabilité de l'irrigation.

1. INTRODUCTION

Irrigation systems are evolving toward increasing complexity due to the integration of multiple technologies, including pressurized networks, automated control systems, fertigation units and distributed sensing devices. However, the operational management of these systems often remains based on partial information and empirical decision-making.

This situation leads to several inefficiencies:

- lack of visibility on hydraulic performance,
- uneven water distribution,
- excessive energy consumption,
- delayed detection of anomalies,
- limited coordination of field operations.

The need for improved irrigation management is further reinforced by:

- increasing water scarcity,
- rising energy costs,
- climate variability,
- pressure on agricultural productivity.

In this context, there is a growing demand for systems capable of integrating hydraulic modelling and real-time data to support operational decision-making at farm scale. This paper presents an Irrigation Management System (IMS) designed to address these challenges through a combination of hydraulic digital twin modelling, data integration and field operation management.

2. SYSTEM ARCHITECTURE AND METHODOLOGY

2.1 General architecture

The IMS is based on three main components:

1. Data acquisition layer
2. Hydraulic modelling layer
3. Operational management layer

The system is designed to be **plug-and-play**, allowing deployment without major modifications to existing irrigation infrastructures.

2.2 Data acquisition

Data sources include:

- pressure sensors,
- flow meters,
- energy consumption data,
- soil moisture sensors,
- weather data,
- equipment status (valves, pumps, pivots).

Data can be collected from multiple manufacturers and protocols, ensuring interoperability.

2.3 *Hydraulic digital twin*

The core of the system is a **hydraulic digital twin**, which models:

- flow distribution,
- pressure variations,
- head losses,
- interactions between network components.

The model operates continuously and is updated using real-time data. In partially instrumented systems, the model relies on:

- calibrated hydraulic assumptions,
- progressive data enrichment,
- iterative validation.

2.4 *Anomaly detection and diagnosis*

The IMS compares:

- expected hydraulic behaviour (model),
- observed behaviour (field data).

This allows identification of:

- pressure imbalances,
- under-supply areas,
- abnormal losses,
- equipment malfunction.

2.5 *Field operations management*

A key feature of the system is the integration of **field team management**:

- anomalies are prioritised,
- interventions are scheduled,
- alerts are contextualised,
- actions are tracked.

This improves:

- responsiveness,
- coordination,
- efficiency of field operations.

3. FIELD DEPLOYMENT AND CASE STUDIES

The IMS has been deployed across multiple regions:

- Europe,
- West Africa,
- Latin America.

3.1 *Scale of deployment*

- more than 10,000 hectares monitored,
- multiple crop types (banana, sugarcane, horticulture),
- diverse irrigation systems (pivot, drip, mixed networks).

3.2 *Operational conditions*

Deployments include:

- fully instrumented systems,
- partially instrumented networks,
- multi-site operations.

The plug-and-play nature of the system enabled rapid deployment in all contexts.

4. RESULTS AND PERFORMANCE ANALYSIS

4.1 *Water efficiency*

Observed results show:

- water consumption reduction: **10–25%**, depending on initial conditions,
- improved distribution uniformity,
- reduction of over-irrigation.

4.2 *Energy efficiency*

Energy savings range from:

- **10–20%**, mainly due to:
- optimized pressure levels,
- improved pump scheduling,
- reduced unnecessary operation.

4.3 *Reliability and maintenance*

The system enabled:

- early detection of anomalies,
- reduction of emergency interventions,
- improved preventive maintenance.

4.4 *Field team performance*

Operational improvements include:

- faster response time,
- reduced travel for diagnostics,
- improved prioritisation of interventions,
- better coordination between teams.

These factors contribute directly to improved irrigation consistency.

5. ECONOMIC ANALYSIS

5.1 *Cost structure*

The IMS requires:

- limited installation cost (plug-and-play),
- minimal infrastructure modification,
- scalable deployment.

5.2 *Return on investment (ROI)*

ROI is driven by:

- reduced water consumption,
- reduced energy costs,
- lower maintenance costs,
- improved operational efficiency,
- yield stabilisation.

Results show:

- payback period: 12 to 18 months,
- strong economic performance across different contexts.

5.3 *Economic resilience*

The system improves resilience by:

- reducing dependency on manual expertise,
- stabilising production,
- improving resource efficiency.

6. DISCUSSION

The results demonstrate that combining:

- hydraulic modelling,
- real-time data,
- operational management,

provides a robust framework for improving irrigation systems. Unlike traditional approaches, the IMS:

- does not require full instrumentation,
- can be deployed incrementally,
- integrates technical and operational aspects.

However, challenges remain:

- data quality variability,
- need for calibration,
- training of operators.

7. CONCLUSION

The Irrigation Management System presented in this paper provides a practical and scalable solution for improving irrigation performance at farm and network scale.

Key outcomes include:

- improved water and energy efficiency,
- enhanced operational management,
- rapid economic return,
- adaptability to different contexts.

The integration of hydraulic digital twins with real-time data and field operations management represents a significant step toward more efficient and resilient irrigation systems.

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